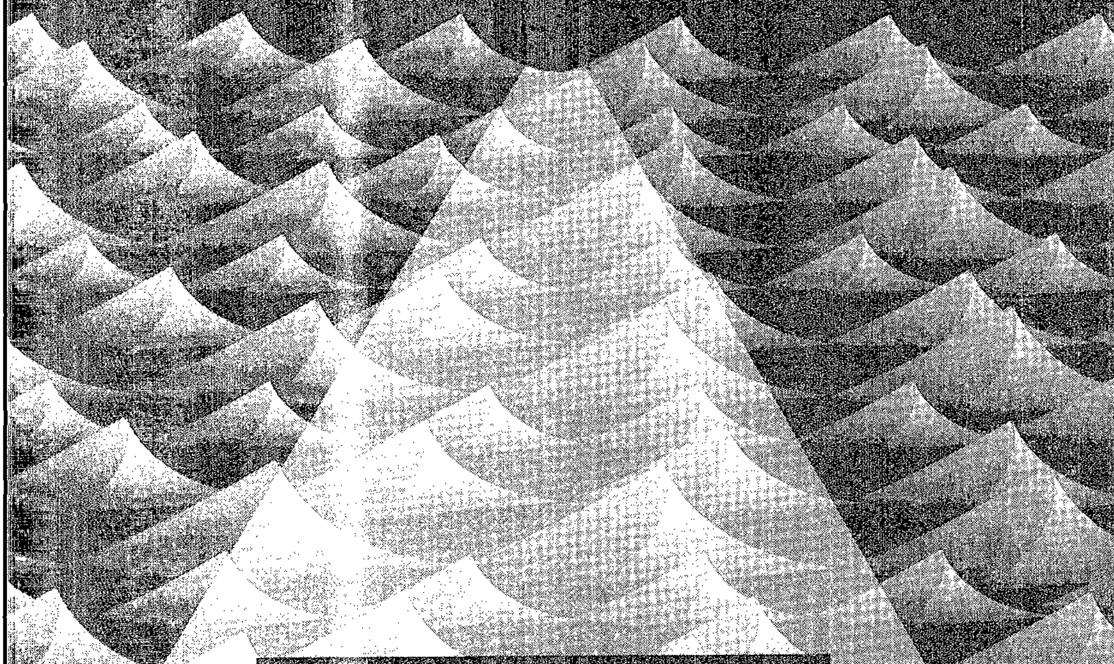
Technology for the United States Navy and Marine Corps, 2000-2035

Becoming a 21st-Century Force

VOLUME 6 Platforms



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Technology for the United States Navy and Marine Corps, 2000-2035

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VOLUME 6 Platforms

Panel on Platforms
Committee on Technology for Future Naval Forces
Naval Studies Board
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

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Preface

This report is part of the nine-volume series entitled *Technology for the United States Navy and Marine Corps, 2000-2035: Becoming a 21st-Century Force.* The series is the product of an 18-month study requested by the Chief of Naval Operations. To carry out this study, eight technical panels were organized under the Committee on Technology for Future Naval Forces to examine all of the specific technical areas called out in the terms of reference.

On November 28, 1995, the Chief of Naval Operations (CNO) requested that the National Research Council initiate, through its Naval Studies Board, a thorough examination of the impact of advancing technology on the form and capability of the naval forces to the year 2035. The terms of reference of the study specifically asked for an identification of "present and emerging technologies that relate to the full breadth of Navy and Marine Corps mission capabilities," with specific attention to "(1) information warfare, electronic warfare, and the use of surveillance assets; (2) mine warfare and submarine warfare; (3) Navy and Marine Corps weaponry in the context of effectiveness on target; [and] (4) issues in caring for and maximizing effectiveness of Navy and Marine Corps human resources." Ten specific technical areas were identified to which attention should be broadly directed. The CNO's letter of request with the full terms of reference is given in Appendix A of this report.

The Panel on Platforms was constituted to address technology issues related to military platforms—surface, air, and subsurface—that will support future Navy and Marine Corps missions. As part of its effort, particular attention was directed to item 6 of the terms of reference:

> Navy and Marine Corps platforms, including propulsion systems, should be evaluated for suitability to future missions and operating environments. For

example, compliance with environmental issues is becoming increasingly expensive for the naval service and affects operations. The review should take known issues into account and anticipate those likely to affect the Navy and Marine Corps in the future.

The terms of reference for the study charged the Panel on Platforms with examining how new directions in technology development can be brought to bear to enhance the effectiveness of future naval platforms, taking note of recent changes in the national security environment (threat, tasking, resources) and those that can be expected to occur in the future. The panel realized that (1) resource availability will be the controlling factor; (2) the threat will remain diffuse in origin and broad in scope, with a consequent need for a viable, up-to-date naval force structure; and (3) the Navy and Marine Corps missions in the uncertain future will continue to be defined broadly as the application of sea power in the national interest.

Panel membership included expertise in systems engineering; naval architecture; electrical and mechanical engineering; propulsion engineering; ship, aircraft, and submarine design and manufacturing; large enterprise management; and direct operational experience. The panel held 10 meetings over the course of a year, during which it received input from scientists, engineers, and decisionmakers from government, industry, and academia with specialized expertise in platform technologies.

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Executive Summary

INTRODUCTION

The Navy and Marine Corps will have to replace the majority of their warfighting equipment in the next 35 years. This will have to be accomplished within the fiscal constraints imposed by an overall military budget that is significantly lower, in real terms, than that available during the period of the last military buildup in the 1980s. Current thinking on this subject suggests that the required replenishment of Navy and Marine Corps capital assets in the face of such constraints can be accomplished only by reducing operations and support costs and by using commercial standards where acceptable, modular construction, and new technologies that offer lower total life-cycle costs. The expectation is that the savings accrued by implementing these concepts and technologies will be available to fund the R&D and acquisition of new surface, subsurface, and air platforms to support Navy and Marine Corps missions.

Based on briefings and discussions conducted by the Panel on Platforms during the course of this study, there appears to be a sincere desire, as well as a requirement, by the Department of the Navy to maintain a balanced naval capability. This will be an extremely difficult task to fulfill in the fiscal environment facing the Department of Defense (DOD) over the next five years.

Despite the changed fiscal environment, the Navy Department still retains its historic missions: sea control, power projection, deterrence, forward presence, and sea lift. A detailed characterization of these missions is included in the

description of Navy and Marine Corps operating doctrine in a paper entitled "Forward...From the Sea."[1]

With the end of the Cold War, the potential threats that the Navy and Marine Corps must be prepared to counter have become significantly more diverse. The unpredictability of the timing, direction, and lethality of various potential adversaries requires the Navy Department to maintain both a sufficient force structure and an adequate pace of modernization. Since it is impossible to predict precisely the military environment of 2035, the planner must provide technologies that can be adopted and adapted to support concepts that emerge as time passes.

VISION FOR 2035

The Navy Department will have to create new platform concepts capable of performing its missions in a timely and cost-effective way. The challenges faced by the Navy and Marine Corps in this era are similar to those faced by the Navy in making the transition from sail to steam and, later, to carrier jet aircraft. Addressing these challenges will require the following actions:

- A commitment to depart from traditional solutions,
- A concerted effort to develop enabling technologies, and
- A plan to make the transition from the old to the new.

Each of these tenets is reflected in the recommendations made in this report.

The Navy has adapted to its sharply reduced budget by decommissioning ships and aircraft that still have significant operational capability. In the context of this downsizing of U.S. naval forces, a decision was made to support the production base in Navy-unique technology and production capabilities. Shipbuilding is a case in point. There is a two-edged sword at play here. On the one hand, there is a need to maintain momentum in the shipbuilding industry in the face of reduced procurement. On the other, decreased procurement volume drives unit cost up.

To offset and regain funds for recapitalization it is essential for the Navy Department to have a comprehensive plan that minimizes manning, infrastructure, and all life-cycle support costs. Ideally, this should be coupled to a broad agreement with DOD and Congress to allow recaptured funds to be applied to the Navy and Marine Corps recapitalization program.

COMMON THRUSTS FOR PLATFORMS

The Panel on Platforms concluded that there is a set of common thrusts—

[1] Department of the Navy. 1994. "Forward...From the Sea," U.S. Government Printing Office, Washington, D.C.

stealth, automation, minimal manning, affordability, fluid and flow control, and off-board vehicles—that can be pursued over the next several years to maximize the operational performance and affordability of future naval platforms. These thrusts can be pursued most effectively within the context of a systems engineering approach to the adoption of new technology, both as individual technology components and as an integrated whole.

Stealth

One obvious driver for the future of naval warfare is the combined effect of developments in sensor technology and the proliferation of this technology. The expected improvements in target acquisition, coupled with advanced missilery, mines, torpedoes, and other weapons, put a high premium on the avoidance of detection, whether in the littoral or on the high seas. Stealth technologies and the ability to apply them in a seamless manner offer the best means of maintaining an effective naval presence in the face of a hostile adversary. Most of the specifics of technology relating to low observables are necessarily highly classified. The discussion in this report is restricted to general principles that derive from basic physics and to areas that are not highly classified.

Automation

The technology associated with automatic operation or control of equipment and processes has made and continues to make great advances. The application of condition-based monitoring and the maintenance of components and systems often associated with automation will increase the reliability of equipment. Improved detection of dangerous conditions will revolutionize damage control. To realize optimum gains, open architecture systems should be pursued in a systematic and integrated fashion down to the component level. Besides the advantages of efficient operation and reliability, aggressive utilization of intelligent automation in naval ships and submarines will enable crew and life-cycle cost reductions.

Minimal Manning

Minimizing platform manning will have a significant impact on the life-cycle costs of Navy ships. The largest single factor in ship cost is the crew, which involves not only direct salary, benefits, and training costs for Navy personnel, but also the indirect expense of the manpower infrastructure, bases, barracks, commissaries, retirement plans, and so forth. Platform acquisition costs can also be reduced through ship design with a specific focus on reductions in requirements for berthing, food services, air conditioning, and so on.

Affordability

Cost is critical, and for the foreseeable future it will be a major factor in determining the size and structure of the armed forces. Unit cost is related inversely to force size; therefore, unit cost has to be minimized. The most visible component of system cost is initial acquisition, which includes both design and production; therefore savings should be sought in both areas in parallel. Life-cycle costs can be minimized through careful consideration of crew size, maintenance requirements, modularity, and fuel consumption.

Fluid and Flow Control

Fluid flow phenomena are critical to all aspects of platforms for naval warfare. If the flows of air and water about the bodies of ships, aircraft, and submarines could be better understood and brought under control, their efficiency and maneuverability could be improved substantially. Similarly, understanding and control of hot gas flows would enable major gains in engine performance, efficiency, and reliability. Ship and aircraft auxiliary and utility systems could also be improved. As an example of the potential, experiments and calculations indicate that platform drag might be reduced measurably if flow turbulence and separation could be suppressed over most of the surface.

A major key to achieving these gains for all platforms and propulsion systems lies in a markedly improved understanding of the basic physics of fluid flow and improved techniques in computational fluid dynamics (CFD) to permit engineers to understand and predict the effect of mechanisms to control flows. The principal need is for improved models of turbulence for Reynolds-averaged Navier-Stokes simulations, and when available, large-eddy simulations. This should be a high priority for the Department of the Navy. This need is well recognized in the CFD community and is the subject of active research, but more work is necessary. In particular, strong Navy Department guidance and support are essential to ensure that suitable turbulence models will be developed to meet the full range of needs that are of most direct concern to naval forces. This will require a vigorous, focused, integrated program of theoretical investigation, experiment, and computation.

Off-board Vehicles

Autonomous adjunct vehicles, both underwater and aerial, will play an increasingly important role in naval warfare. Unmanned aerial vehicles (UAVs) will be employed across the mission spectrum, starting with reconnaissance, then in support, and finally in selected lethal roles. Unmanned underwater vehicles (UUVs) can extend a submarine's battle space significantly and add mission abilities of great importance, while serving to reduce risk for the submarine.

PLATFORM TECHNOLOGY—IMPACT AND RECOMMENDATIONS

Platform technologies set the bounds on the performance of ships, aircraft, and submarines and are thus fundamental to the consideration of all naval and naval aviation technology. The design, production, and useful operating life of naval platforms typically span several decades. The long time lines associated with the implementation of new platform technologies, together with their fundamental impact on warfighting effectiveness, necessitate a systematic, top-to-bottom approach to their adoption. To integrate advanced technology into future naval platforms, the Navy Department should implement a focused effort that includes clearly defined goals and schedules, industry-government partnerships, and stable funding. The Integrated High Performance Turbine Engine Technology (IHPTET) program is a good model for this type of effort. The demonstrated success of this program in the past cannot be overstated. The Panel on Platforms suggests that the IHPTET approach to technology development be considered as the bridge to the future in several technology fields of relevance to the Navy and Marine Corps.

Surface Platforms

Impact of Surface Technology Initiatives

Implementation of the technologies discussed in this report should enable the Department of the Navy to create an advanced and highly effective fleet at an affordable cost. There are several key technologies that could enable significant signature reduction, which would in turn increase the warfighting effectiveness of surface ships. Likewise, critical advances in automation components and architecture and in the fielding of electric drive should reduce both acquisition and life-cycle costs while enhancing combat effectiveness. These technologies support the entire potential family of future ships from amphibious vehicles, to surface combatants, to aircraft carriers. The following are the panel's highest-priority recommendations with regard to developing and exploiting the advanced platform technologies that will enable the Navy and Marine Corps to accomplish their missions in the future. Additional recommendations are presented in the main text of this volume.

Ship Technology Recommendations

- To minimize manning, increase reliability and survivability, enhance system upgradability, and reduce life-cycle costs, develop and introduce component-level, intelligent, distributed ship systems automation technology, including the following:

    —Microprocessor-based intelligent sensors and actuators;

—Reliable secure communications at all levels, including peer to peer;

—Intelligent operation, monitoring, maintenance, and damage control doctrine; and

—Commercial open architecture systems adaptations.

- Aggressively pursue integrated electric drive power and propulsion systems; develop and exploit quiet, high-density permanent magnet propulsion motors; exploit advances in semiconductor technology to develop power electronic building blocks; and begin at-sea testing and evaluation of system performance. These approaches offer high potential for reducing signatures and decreasing life-cycle costs.
- Expand signature reduction initiatives in the following areas:

—Composite materials,

—Advanced hydrodynamics and power systems,

—Closed-loop degaussing, and

—Advanced hull forms.

Air Platforms

Impact of Air Technology Initiatives

Developing the enabling technologies for more advanced naval aviation platforms should facilitate the development of a more cost-efficient force than we have today. Expanded air platform options enabled by new technologies include (1) a more vertical force—vertical takeoff and landing, short takeoff and vertical landing, and short takeoff and landing; (2) widespread use of land- and sea-based UAVs for surveillance, reconnaissance, targeting, and later, lethal missions; and (3) utilitarian aerial trucks to be employed as weapons carriers, target designators, and sensor platforms. Commanders will be accorded vastly increased flexibility in aircraft carrier (CV) deck loading such that a CV can operate as an all-strike ship or, alternatively, solely in a support role. Finally, the range of viable CV sizes and configurations can be widened considerably, from Nimitz size down to a much smaller ship, each operating the same types of aircraft.

Air Technology Recommendations

- Pursue technologies that reduce takeoff and landing footprints and improve the payload range and the endurance of manned and unmanned aerial vehicles:

—Slow-speed laminar flow control;

—High-lift aerodynamics;

—Lightweight, high-strength composites;

—Core engine performance enhancement;

—Variable cycle engines;

—Small, high-performance, heavy-fuel engines; and
—Integrated flight and propulsion control.

• Exploit commercial developments in high-capacity, long-range data links.

• Emphasize technology developments focused on reducing the cost of enhanced survivability.

• Pursue technologies that contribute to lower-cost design and manufacturing:

—Dynamic electronic prototyping; and
—Reduced-cost, low-rate production.

Subsurface Platforms

Impact of Submarine Initiatives

The infusion of new technology into both new and existing submarines should continue to provide a stealthy platform with great mobility, endurance, payload potential, and survivability. Throughout the development, application, and coordination of these and other technologies, great emphasis must be given to reducing submarine acquisition and life-cycle costs. Greater affordability can be facilitated through the use of technology to minimize design and construction costs, reduce manning, cut maintenance requirements, and provide the ready insertion of performance upgrades over the submarine's lifetime.

Submarine Technology Recommendations

• Exploit the spectrum of payload technologies to provide future submarines with an integrated payload system that is flexible and modular and can covertly carry, launch, and recover a wide range of future weapons, sensors, vehicles, and forces. Develop submarine-launched off-board vehicles, both UAVs and UUVs, for use across all mission areas. Deliberate growth of this adjunct capability can utilize a two-track approach of cheap, expendable systems and expensive, reusable ones.

• Aggressively pursue a stable, extensive R&D program for the continuing analysis and guaranteed quality of submarine stealth. This program must address all aspects of stealth technology, including hydrodynamics, acoustics, nonacoustics, and signal emissions, in an integrated systems approach.

• Upgrade submarine sensors and their connectivity, thereby improving the submarine's ability to sense, process, and fuse information through the application of rapidly advancing technologies: fiber optics, acoustics and nonacoustics, lasers, high-speed computers, and other innovations.

• Significantly improve submarine power density as a key to the improvement of payload capacity, warfighting effectiveness, and survivability. The space and weight fraction dedicated to energy production and distribution must be

reduced in submarine main power, auxiliary power, weapons, and off-board vehicles.

Environmental Issues

The Panel on Platforms was asked to examine how technology can be utilized to ameliorate the environmental impact of future naval platforms, and in so doing put specific emphasis on shipboard waste treatment systems to minimize water pollution. The panel decided to treat the reduction of air emissions as a component of advanced propulsion system development for both naval vessels and aircraft. Current (mature) technologies for shipboard waste treatment such as plastics processors, pulpers or shredders, and liquid filtration systems, which have long enjoyed development under the auspices of Navy laboratories, are already at the implementation stage in many larger vessel classes. The enabling technologies considered, including supercritical water oxidation, advanced incineration, and plasma arc pyrolysis, have differing benefits and constraints in terms of power requirements, weight and space, efficiency, operator expertise required, and signature implications. Moreover, the reliability of treatment systems, particularly a single treatment system, seriously affects the suitability of the system for shipboard implementation. As a consequence, a series of smaller-scale, waste stream-specific technologies (including plastics processors, incinerators, and liquid filtration systems), which can be driven by existing energy sources (e.g., JP-5 or diesel fuel), is recommended for future development and implementation, in contrast to larger-scale, energy-intensive devices such as the plasma-based systems.

It is the conclusion of this panel that the shipboard waste treatment systems for future warships should be designed for easy implementation into the platform. Power requirements must not necessitate external shipboard generators and the associated increase in space required.

CONCLUSION

In conclusion, the panel believes that there are many technologies available to the Department of the Navy for future platform design and implementation options. These opportunities, if pursued in an integrated and systematic way, will allow decisionmakers of the future to make choices based on changing requirements and affordability constraints.

1

Introduction

The terms of reference for this study charged the Panel on Platforms to examine how new directions in technology development can be brought to bear to enhance the effectiveness of future naval platforms, taking note of recent changes in the national security environment (threat, tasking, resources) and those that can be expected to occur in the future. The panel concluded that (1) resource availability will be the controlling factor; (2) the threat will remain diffuse in origin and broad in scope, with a consequent need for a viable, up-to-date naval force structure; and (3) the Navy and Marine Corps missions in the uncertain future will continue to be defined broadly as the application of sea power in the national interest.

From that foundation of real funding constraints, ill-defined but worrisome threats, and continuity in the basic mission of the Department of the Navy, the panel addressed, in terms of surface, air, and subsurface platforms, the specific charges in the terms of reference for the application of emergent technologies to do the following:

1. Enhance capabilities, and identify Navy-unique R&D needs;
2. Concentrate on defense against information and electronic warfare;
3. Treat mine and submarine warfare as serious future threats;
4. Advance cruise and ballistic missile offense and defense;
5. Improve capabilities across the range of weaponry;
6. Evaluate the suitability of propulsion systems to future missions, and consider environmental issues;
7. Consider requirements for nontraditional roles;

8. Optimize the efficient and effective use of personnel;
9. Evaluate technology to enhance quality of life; and
10. Review the merits of modeling and simulations.

OPERATIONS OTHER THAN WAR

The changed security environment will mean that the Navy and Marine Corps will be tasked increasingly with nontraditional, noncombat missions. Such operations other than war (OOTW) include the following:

- Humanitarian or noncombatant evacuation;
- Search and rescue or disaster response;
- Response to environmental threats;
- Fisheries enforcement;
- Piracy prevention;
- Counternarcotics operations;
- Military assistance;
- Tanker escort;
- Information warfare and communications intelligence;
- Embargo enforcement;
- Smuggling interdiction;
- Biological or chemical material interdiction;
- Nuclear weapons or nuclear material interdiction;
- Actions to counter insurgency, coups, and uprisings; and
- Bomb detection.

It is possible that OOTW missions will represent the major portion of the deployed time of future naval platforms throughout their operating lives. Accordingly, OOTW mission requirements should be taken into consideration in the design of future platforms, and the Navy Department research and development portfolio should include technology development targeted at these requirements. OOTW missions may require the following:

- Special outfitting of ships and submarines including methods for rapidly and safely deploying and retrieving boarding teams and high-speed watercraft, medical triage facilities, disease control or quarantine methods and equipment, multipurpose interchangeable general-purpose spaces, underwater visual capabilities and equipment, pollution control or containment methods and equipment, special weapons, detainment methods, magazines, and other unique law enforcement tools and off-ship firefighting equipment;
- Off-board or remote and on-board identification and detection capabilities (night vision, infrared, long-range visual, x-ray) for counternarcotics opera-

tions, human bodies, bomb and nuclear material, chemical and biological material, seismographic activity, and so forth;

- Enhanced, specialized connectivity, communications, and data links with nontraditional sources (intelligence, law enforcement, medical, and communications intelligence missions); and
- Close-in maneuverability and navigation capabilities and efficient ingress and egress routes.

OBJECTIVES FOR TECHNOLOGICAL ADVANCE

In identifying key enabling technologies that would benefit the Navy and Marine Corps, the panel kept in mind three principles throughout the course of the study:

1. In aggregate, the selected technologies must contribute to life-cycle cost reduction. For example, performance improvements are desirable, but not if they seriously jeopardize the life-cycle cost reduction goal.
2. Each technology must make a significant difference. Marginal improvements have been rejected as not being worth the cost.
3. Essential mission capabilities should not be eroded.

The panel sees no technology "showstoppers" that would prevent the Navy from making substantial improvements in the design of future naval platforms. Rather, the impediments to change come from culture and policy as well as budget constraints if funds allocated to technology development turn out to be either inadequate or unstable over time. The panel anticipates that the principal problem will be that of countering the natural human tendency to resist change—a trait reinforced in the several platform communities by an understandable reluctance to give up that which is seen as familiar, useful, reliable, combat proven, and essential to one's professional career. Further, the panel expects that responsible operational commanders and those in Washington, responding to systems requirements generated by the fleet, will exhibit skepticism over changes along the lines of those offered here, particularly if they are seen as too dramatic or too quickly forgoing familiar and proven types of ships, submarines, and air vehicles. Such skepticism is viewed by the panel as being healthy and useful to the development of a cost-efficient future naval force that builds on current capability.

In its deliberations, the panel made no attempt to match technology recommendations with anticipated specific future threats and possible political scenarios. Trying to predict trends and events far in the future was outside the scope of its activities. Instead, the panel focused on technologies that, if developed and applied, could rectify current deficiencies, improve overall combat capabilities, apply across a broad range of missions and platforms, and reduce acquisition and

operating costs. Further, the panel believed that the Navy Department should not attempt now to predict or ordain what kinds of platforms to buy for the year 2035. Instead, the prudent cost-beneficial approach is to lay out a sound plan to develop the recommended enabling technologies and then, as success is demonstrated, begin to formulate platform concepts that exploit the potential these technologies offer.

2

Surface Platform Technology

OVERVIEW OF FUTURE SURFACE PLATFORM TECHNOLOGY

Within the next three decades the U.S. Navy must be able to produce surface combatants capable of conducting all types of naval missions with minimal crews and with stealth levels that allow combat operations to be conducted with the lowest possible risk. The characteristics of 21st-century naval platforms will be influenced by three primary factors: (1) resources allocated for defense, (2) technology, and (3) evolving threats. These are not independent variables. By leveraging commercially available technology with focused development targeted on the unique needs of the Navy and Marine Corps, the Department of the Navy can create an effective and affordable military capability. Some investment is required, however, in order to pursue the available opportunities that emerging technologies afford. Failure to allocate resources to develop new platform technologies will mean continuation of the status quo into the future.

It is anticipated that the technologies described in this report, such as advanced hull forms, integrated electric power and propulsion systems, stealth, and automation, will be applicable to all surface platforms envisioned for the early part of the 21st century. The panel anticipates the following platform types:

- The aircraft carrier of this era will continue to fulfill the missions of deterrence and sustainable strike combat power. A significant reduction in manning[1] level with concomitant life-cycle cost reductions will be made to both ship

[1] The term "manning" is used as a convenient, generic shorthand for assigning personnel, male or female, to organizational and technical tasks within major systems and support bases.

and airwing. Engineering plants could include high-power-density nuclear power plants with integrated electric power and propulsion systems. Steam catapults may have given way to lighter, less manpower-intensive systems (candidate systems include electromagnetic and internal combustion catapults). The carrier could be configured to handle conventional takeoff and landing, short takeoff and vertical landing, vertical takeoff and landing, and pilotless aircraft. It will have a complete mission planning capability for all weapon systems (joint weapons) and may be capable of controlling one or more arsenal ships.

- The surface warfare combatant will be a rugged, survivable, highly automated, low-signature platform with an efficient hull form and electric drive. The ship will be minimally manned and will have the capability to deliver ordnance against air, surface, and subsurface targets (the linear descendant of the Fletcher). It will have a mission planning capability and an ability to guide either surface- or air-launched weapons. It will be capable of operating independently and in conjunction with one or more arsenal ship types and aircraft carrier battle groups. Some surface ships will have guns and missiles for naval surface fire support, as well as antiaircraft warfare, antisubmarine warfare, and theater missile defense mission capabilities.
- A new ship type, the arsenal ship, will project any and all of the vertical launch system (VLS) weapons of the 21st century. It will support all mission areas for which there is a VLS weapon. The weapon system of this ship type will be controlled remotely from another ship, a land station, or a control aircraft. Primary ship defense of this type will derive from low signatures in all areas: radar, acoustic, magnetic, infrared (IR), and visible.
- Amphibious platforms will be configured to support littoral warfare. It is envisioned that two classes will dominate: (1) a large ship similar to today's air-capable ships carrying advanced amphibious assault vehicles, landing craft air cushioned, rotary wing aircraft, and VLS for protection, strike, and remote launch; and (2) a smaller, dedicated platform to support Marine Corps concepts such as Sea Dragon.

The following are the technology focus areas for major efforts with respect to surface platforms:

- Minimal manning through automation,
- Integrated electric power and propulsion systems,
- Signature reduction,
- Modular design,
- Environmental control,
- Aircraft catapults, and
- Indigenous self-defense.

TECHNOLOGY FOCUS AREAS

Minimal Manning Through Automation

Objective

In addressing affordability while maintaining functionality, achieving minimal manning is the most significant factor in driving down ship system life-cycle costs. Not only must normal watch standing, machinery monitoring, and maintenance be accomplished with lower numbers of personnel, but so also must casualty and damage control for survivability. The logistics operations for maintaining ships at sea are essential efforts that can profit from a more automated ship through the greater availability of timely information about the ship's systems. Automation can support these reductions while ensuring adequate performance. Even in the case of damage control, the capabilities that automation provides, especially in new designs, offer strong encouragement that truly automated, low-manpower ships are practical. As a result, ships and their systems can be operated and fought remotely.

Enabling Technology: Automation and Control

The purpose of automation is to provide access to information and control at all desired levels and points in a ship. By and large, present Navy automation programs address issues from the command level down, relying on traditional local area network (LAN) protocols and the use of technology developed to support the management and manipulation of high-level information systems. Current approaches toward machinery automation and automated damage control seek to better sense and collect information. This information is generally routed to central stations where evaluation and response functions reside. True distributed intelligent sensing, reasoning, and response are not yet available. At the tactical systems level, the concept of distributed intelligent control with modular software and the use of standard interface structures is being adopted. The reliance on relatively disparate proprietary approaches is giving way to systems that employ commercially available hardware and software with standard interfaces and open architectures. At the tactical and system monitoring levels, these LAN-based, modular, open architecture systems offer much in the way of improved reliability, reduced cost, and upgrade capability. The LAN-based approach loses its effectiveness at the component level, however, where the per-node hardware and software costs become excessive and the complexity of developing software embedded in a relatively few computers running a LAN protocol becomes unmanageable. The reason is simply that the nature of the functions and communications at the component level differs considerably from what is often required at the tactical level.

Truly distributed control systems have long been a dream that has evaded realization because of the high costs of addressing large, complex systems down to the component level. Recently, a powerful set of tools and components in the form of an open architecture, local operating network (LON) have emerged from the commercial sector to provide a control bus environment at the component level. With the emergence of a fully exploited control bus, component-level intelligent distributed control systems (CLIDCS) can provide sensing, thinking, and acting with full access to information and control at any level in the control system hierarchy. This results in increased flexibility, survivability, and cost-effectiveness over other approaches. CLIDCS consists of a cost-effective, commercial off-the-shelf (COTS), open architecture system including communications processors, transceivers, microcontrollers, and open network protocols that permit each sensor and actuator device in a ship's system to connect directly to any other node through a peer-to-peer communications network, while avoiding the essentially point-to-point networks common to other approaches. This arrangement provides local intelligence through the use of embedded microprocessors at each node (every important electromechanical device) in the system, the ability of each intelligent node to communicate directly to any other node on the control network as required, and as a result, transparent access to information and control at the component level or any other desired level. Software changes can be made at individual nodes, thus avoiding disruptive changes common to monolithic software architectures. Depending on the application, a node may manage one or several system sensor and actuator signals.

If this emerging technology can be identified, developed, demonstrated, and implemented in a timely fashion, CLIDCS will be the essential enabler of increased performance and reduced life-cycle costs through minimal manning. At a minimum, the use of this approach should dramatically reduce control system wiring as the point-to-point technique common to previous-generation control systems is replaced by the serial linked array of nodes that communicate using a protocol optimized for short, high-reliability command-type messages. Interoperable protocols allow future upgrades without major system upheavals. Beyond this, with intelligence residing at each node, sensing, computation, and actuator functionality may be distributed as desired throughout the system. Information can be available transparently throughout the network, thus providing a virtual information fabric for the system. Current costs (on the order of $200 for microcontrollers, communications protocol, and transceivers per node) are kept low through the use of high-volume, commercially available technology designed specifically for control. Control from, and communications with, higher levels of command can be provided through gateways between the CLIDCS system and the higher control levels. The proposed CLIDCS approach thus complements current and proposed Navy shipboard automation systems at higher levels (e.g., the Standard Machinery Control System). The result could be a common, open control architecture that will be both scalable and interoperable to

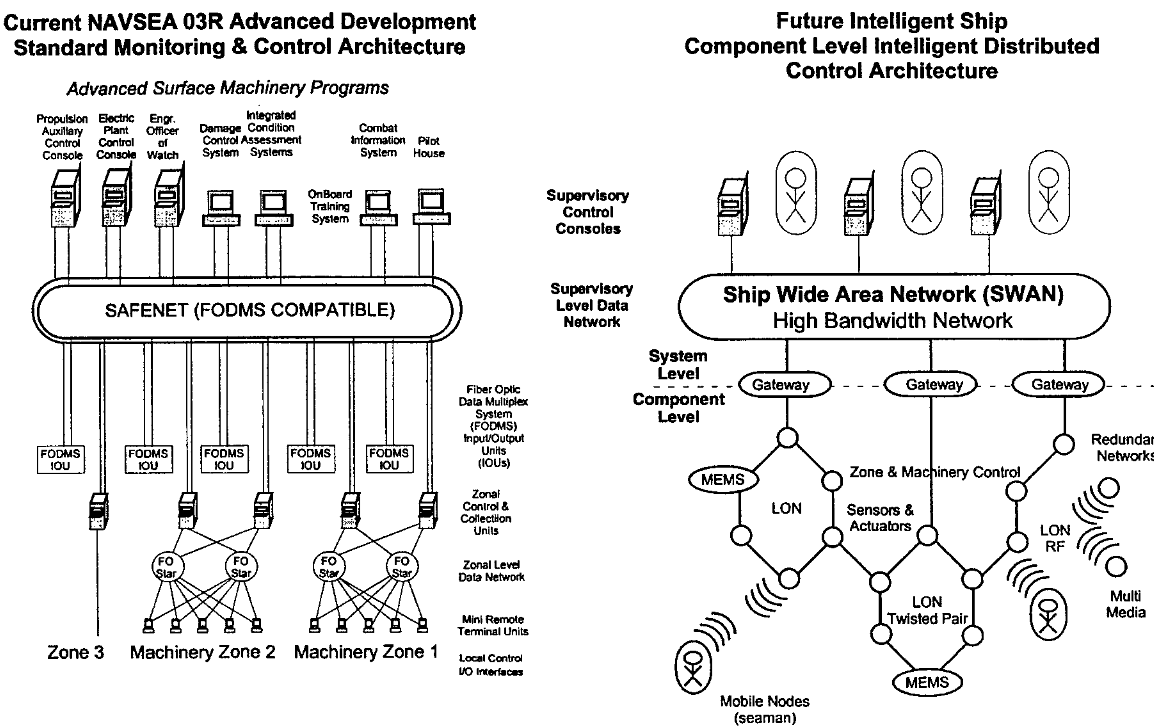


FIGURE 2.1 Schematic comparison of current and future control architectures. SOURCE: Program review presentation to Naval Surface Warfare Center, Carderock Division, by Dr. Samuel Smith, Department of Ocean Engineering, Florida Atlantic University, Boca Raton, Fla., March 11-13, 1997.

support applications across platform types as well as to accommodate future system growth. Figure 2.1 shows a schematic representation of the Navy's current design of the Advanced Development Standard Monitoring and Control Architecture and a conceptual design of a CLIDCS system.

Although CLIDCS is a new approach for ship automation, a broad and rapidly growing market of factory, building, and transportation system applications currently exists. Furthermore, systems of this type and of comparable complexity are currently used in operating autonomous unmanned undersea vehicles developed and operated with Navy funding.

Benefits

Machinery Control

Future Navy ships will be minimally manned. Highly automated ships will be achievable only if affordable intelligence is present wherever the combination of sensing, computation, actuation, and communications (functions currently performed by sailors) is required. Such automation will make it possible to have a ship's functions carried out with little more than the direct commands of its relatively smaller crew. Ship systems will function in the background to provide support for the crew or to provide ship system response directed by the crew. Maintenance problems with ship equipment will be detected through intelligent condition-based monitoring in time to provide maintenance by special traveling at-sea teams with timely logistical and technical support either at sea or from shore. Equipment redundancy and durability will support the automation approach. Ship crews will likely do much less routine machinery maintenance and repair than is the case today.

Minimal ship crews will permit a reduction in hotel requirements. As a consequence, ships will be designed with more attention to their offensive missions and survivability, while attention given to the crew will be focused more on providing greater functionality, survivability, and comfort than are currently possible.

Damage Control

Ship survivability can be enhanced through the use of integrated intelligent sensing and action systems for rapidly and automatically detecting, characterizing, and controlling fire, flooding, and structural damage. Future ships may be relatively uninhabited, thus permitting focused design efforts aimed toward achieving heightened ship self-protection, including the inerting of spaces, secure compartmentalization, self-healing structural boundaries, and self-sealing fire and flooding control or information networks. Enhanced functionality could be made available either in anticipation of a developing threat or as a result of a

damage event. Relative to today, ships' crews can be much less personally involved in confronting ship damage control emergencies because the ship will be designed to limit damage inherently and to react automatically to damage threats as they occur. Ships' crews would be protected in secure facilities from which they are able to continue combat operations while assessing and managing overall ship conditions.

Potential Impact for the Future Navy

Dependable, cost-effective CLIDCS will transition maintenance, evaluation, and damage control from manual to automated and intelligent, from people doing tasks to people commanding and monitoring tasks, imbuing systems with the ability to sense, reason, act, reconfigure, and share information and status. The impact on the future Navy will include the following:

1. Minimal manning capabilities with enhanced inherent readiness and survivability;
2. Modular, interoperable ship system design for adaptability of next-generation technology;
3. Automated, conditioned-based monitoring and maintenance;
4. Greater integration of at-sea systems with logistical support;
5. Significant improvements in damage characterization and control; and
6. Greater damage containment and control through enhanced compartmentalization, modularity, and system interoperability.

The state of the rapidly developing CLIDCS technology and its availability in the commercial marketplace are such that a great deal can be accomplished in terms of ship automation.

Integrated Electric Power and Propulsion System

Objective

The objective is to capitalize on advances in permanent magnet material technology and in power electronics that are making alternatives available for power generation and distribution for ship propulsion, weapons, and auxiliary systems. Practical demonstration at sea of electric drive with an integrated power system is required in order to develop the mature technology that could be delivered to the fleet. While directed energy weapons tied to integrated power systems require further development, many integrated electric power and propulsion system technologies are ready for at-sea demonstrations in the near term. Such demonstrations should clarify any outstanding issues associated with utilizing

these advances. The Navy could then reap the advantages of improved performance with improved affordability.

Enabling Technology

The combination of advanced permanent magnet materials and power electronics enables affordable, high-performance, electric drive ship propulsion with a fully integrated power system. The integrated power system includes power generation (for both propulsion and ship service applications), zonal electric power distribution, power conversion within each ship module for servicing user equipment, and total system monitoring and control.

In the area of permanent magnet material, neodymium iron boron has higher field strength and lower costs than samarium cobalt, the previous permanent magnet material of choice. Widespread use of these magnets in commercial applications is providing the business base to drive down magnet costs.

Insulated gate bipolar transistors (IGBTs) are gaining widespread commercial use today in power electronic applications. Power converters using IGBTs offer advantages in size, weight, noise signatures, complexity, and affordability relative to conventional power conversion technology. Further advances in power electronics are promised by metal oxide semiconductor-controlled thyristor (MCT) technology. With the reductions in size, weight, complexity, and cost promised by MCTs, a revolution in electronics dubbed "power electronic building blocks" (PEBBs) is promised. PEBBs can be thought of as the integrated circuit of power electronics. A PEBB converts source power into that required by the load and provides programmable system control of the load as well. PEBBs can be useful in such diverse applications as motor controllers, power supplies, bus transfer switches, circuit breakers, actuators, adjustable speed drives, and power inverters or converters. Commercial interest in these applications can be expected to provide the business base and unit volume necessary to drive down costs.

Benefits

These technologies promise benefits in the areas of affordability, arrangement flexibility, power density, increased ship payload, and quieting.

Affordability

Commercial use of these technologies obviously drives down the cost of the elements that comprise the whole. Beyond this, commonality of propulsion motor modules across widespread ship applications offers significant opportunity for cost savings. This commonality would be achieved by producing motor modules in bulk (relative to today's highly individualized propulsion plants) for marine propulsion applications. A single motor module might power a commer-

cial ship, whereas two such modules might power a surface combatant of moderate size. Multiple motor modules per shaft might power a large combatant. In each case, a standard motor module would be the basic propulsion plant building block, with both commercial and naval applications helping broaden the business base to gain the benefits of production in volume.

Propulsion motors can be powered by electricity generated through any number of power sources. Gas turbine generators, diesel generators, steam plants, or any other viable source of electricity can power the electric drive motors. This compatibility further encourages the use of common motor modules for any number of marine applications, commercial as well as naval. With the integrated power system generating both propulsive and ship service power, the design option exists to maximize the ability to drop generators off the line at less than full load speeds to optimize fuel efficiency.

Also contributing to overall ship affordability are the arrangement flexibility, power density, increased payload, and quieting.

Arrangement Flexibility

With electric drive, the prime mover is not tied to the shaft line. This allows ship designers to better balance competing demands for space in the ship's hull. For instance, if a gas turbine prime mover is used in a mechanical drive plant, significant space within the ship's hull must be dedicated to getting air to, and exhaust gases from, the turbines, which are low in the ship, tied into the propulsion shafts. With electric drive, the designer can trade stability and volume concerns and optimize a design that locates the gas turbine generators near the ship's topside to minimize the impact of the intake and exhaust systems.

Power Density

With the permanent magnet motor approach, electric drive can convert a given amount of power while requiring far less weight than a geared mechanical drive system. To further this advantage, the same power generation source that provides electricity to the electric drive motor(s) can provide ship service electricity. Even with redundant power sources for reliability, the advantage lies with electric drive, because redundant ship service and redundant propulsion power systems would become one set of redundant integrated power systems.

Increased Payload

The combination of the power density and arrangement flexibility attributes of electric drive translates into increased payload availability (or conversely, smaller overall ship size for a given payload) for all types of ships.

Quieting

The inherent quietness of solid-state electronics offers cost advantages over conventional power conversion hardware because the need for additional noise control measures is minimized.

Directed energy weapons technology has not yet reached the level of maturity achieved with electric drive and integrated power system technologies, but directed energy weapons and integrated power systems are naturally compatible.

Signature Reduction

General

The increasing general emphasis on the reduction of all naval surface platform signatures (acoustic, radar, magnetic, infrared, and on low observability) is a direct result of the increased performance and lethality of the threat and the move of the Navy into the littorals. The strong emphasis being placed on reduction of the radar cross section of the naval platform is a direct result of the significantly increased performance of the cruise missile and the capabilities of new generation search radars. It can be expected that by 2035 the detection and classification capability of weapons will have advanced significantly beyond what is available today.

Improved weapon seekers across the spectrum of platform signatures will stress the capability of both active and passive defenses. It has long been recognized that decreasing the total signature of a platform decreases the enemy's weapon sensor effectiveness and shrinks the enemy's battle space. For the defender, reduced signature buys space and time.

Senior U.S. Navy policymakers and program managers recognize the importance of signature control and are now establishing ambitious, specific, and quantitative signature goals for platforms and their individual components.

A few fundamental overarching technologies could further the realization of these ambitious signature goals. Pursuing these technologies could result in future naval platforms that are significantly more survivable. The technologies are as follows:

- Composite materials,
- Magnetic signature reduction,
- Drag reduction, and
- Alternative hull forms.

These fundamental technologies and the benefits that will accrue in reducing the signatures and increasing the survivability of future naval platforms are described below. It was the judgment of the panel that these technologies hold the greatest

promise for reducing the overall signature of surface ships. Other technologies, such as those that could reduce infrared (IR) emissions or those that could reduce the acoustic wake formed by cavitating propellers, could also be important but are not discussed in detail here.

Composite Materials and Surface Ship Structure

Objective

A significant reduction in the radar signature of future naval platforms can be enabled by the replacement of steel and/or aluminum with affordable, fire-tolerant, composite material for topside and hull structure.

Enabling Technologies

The use of composites in surface ships' structure enables embedding of antennas and sensors; introduction of special paints, coatings, and various absorbers; introduction of various unique material properties; layering of different materials; tuning of transmission windows in the composite for optimum performance of sensors and emitters; and specific shaping. This can result in a radar signature significantly lower than that of a conventional metal structure.

Current technical challenges preventing the introduction of composite materials into the next generation of naval surface platforms are fire tolerance, toxicity, and electromagnetic interference (EMI) and electromagnetic pulse (EMP) resistance. Additional technical challenges that most likely can be addressed within the current level of effort and funding during the next decade include bonding, grounding, and joining methods; resin and core material development; producibility; strength, weight, and cost parity with aluminum and/or steel; maintenance requirements; and ballistic protection.

The research and development goals of the aircraft industry and other commercial industries are not sufficiently aligned with the goals of the military shipbuilding industry to be relied on to solve the technical challenges peculiar to surface combatants. Commercial industry is not focused on EMI-EMP resistance and significant structural applications for a military environment. In the near and midterm, it is unlikely that the cost-effective application of composite material to topside structure on a surface combatant will result in a significant weight savings compared to aluminum. Weight and cost reductions can be expected to follow the development and initial application of fire-tolerant composite materials for surface combatant ships.

There are several Navy-sponsored advanced technology demonstrations (ATDs) under way that will result in the introduction of composite materials in surface combatant topside applications in a limited manner. These include the advanced enclosed mast-sensor, the multifunction electromagnetic radiation sys-

tem, and the low-observable stack. These ATDs are critical components of the overall effort to introduce composite materials into surface warships in a wholesale manner. Within the current level of effort and funding, however, a solution to fire tolerance, conflagration or flammability, toxicity, combustibility, thermal resistance, and EMI-EMP technical challenges will not be developed in time to allow the application of composites into the next surface combatant program. A focused effort indigenous to the U.S. Navy surface ship community will be required to address the fire tolerance and EMI-EMP technical challenges associated with the application of composites as a primary structural material in naval surface platforms.

Benefits

Utilization of composite material as topside, including deckhouse, stack and mast, and hull structure, in naval surface platforms will enable a reduction in platform signature several magnitudes greater than currently possible for a surface combatant with the traditional steel and/or aluminum material as its primary structure.

Composite materials will enable multifunctional sensors and emitters to be embedded and conformal. Composite materials will also enable specific geometric shaping, treatment, and reflection or absorption characteristics of exposed structure; downsizing or elimination of the mast(s); integration with other topside components such as low-observable intakes or uptakes; and fully enclosed small craft handling equipment, hangars, speakers, lights, and doors. The aggregate result of these changes would be a significant reduction in the radar cross section of a future naval surface platform.

Magnetic Signature Reduction

As the 21st century evolves, U.S. Navy platforms will be increasingly engaged in operations in the littoral—areas close to land and choke points. Potential adversaries can be expected to take advantage of opportunities afforded by the use of cheap and effective mines in the context of littoral warfare.

Bottom mines, both new mines and those left over from past conflicts, often utilize magnetic sensing as their primary sensor technology. Therefore, if Navy platforms (future and existing) can reduce their magnetic signatures significantly, the threat to ships operating in the littoral can be greatly reduced.

Objective

Dramatically reduce the magnetic signature of surface combatants.

Enabling Technology

An appropriate technology may be intelligent, adaptive closed-loop magnetic degaussing. The degaussing system should permit real-time internal monitoring of a platform's magnetic signature for any latitude, any course change, and any combination of internal operating machinery.

Benefits

If significant magnetic signature reduction can be achieved, ships so protected will be considerably less vulnerable to most of the world's existing mine inventory. Moreover, in an effort to engage a ship with a low signature successfully, the adversary can be expected to increase mine sensitivity, which will make mines significantly easier to sweep. Tactically, this should enable U.S. naval forces to operate more effectively in the vicinity of mined areas, particularly those inherent in "brown water" and littoral warfare.

Advanced Hull Forms

Objective

Apply advanced hull form shaping above and below the waterline to provide signature reduction and, where possible, also obtain measurable improvements in seakeeping, speed, and endurance. These improvements along with signature reduction can directly improve the militarily important areas of mission effectiveness, survivability, affordability, and operational availability. Table 2.1 shows the interrelationship between performance and military attributes.

Enabling Technologies

Ongoing naval technology programs in signature reduction offer the opportunity to apply novel hull forms to surface ship platforms in the near term. Advanced materials and computational fluid dynamics (CFD) simulations are among the technologies that can facilitate development of advanced hull forms. Additionally, advances in the understanding and application of concepts such as the hydrofoil small waterplane area ship, wave piercing hull forms, and the small waterplane area twin hull concept offer the potential for major improvements in surface ship configurations.

Benefits

Mission Effectiveness. Signature reduction means that the ship design can be more focused on the offensive mission. Optimized hull shaping both above and

TABLE 2.1 Advanced Hull Form Benefit Matrix

	Performance Attributes			
Military Attributes	Signature Reduction	Seakeeping	Speed	Endurance
Mission effectiveness	X	X	X	X
Survivability	X	X	X	
Affordability	X			X
Operational availability		X	X	X

below the waterline can be used to decrease the potential for detection by opposing forces and increase the potential for avoiding a direct hit if the ship is detected.

Seakeeping improvement delays degradation in mission performance, both hardware and human. Having the ability to put ordnance on target in inclement weather provides significant advantages from the warfighting perspective. The ability to develop hull forms capable of sustained operations at high speed in heavy seas would yield tremendous tactical benefits, and the peak performance of any crew is enhanced if the adverse effects of roll and pitch can be minimized.

Speed enables access to more littoral engagements and cooperative operations and also provides potential advantages relative to the element of surprise. Furthermore, speed allows for coverage of a greater global area with fewer assets.

Survivability. Signature reduction lowers the detection probability. Hull form shaping both above and below the surface can be used to reduce acoustic, wake, and radar signatures dramatically. In addition to reduced detectability, reductions in signature make it more difficult for others to target even when the ship has been detected.

Improved seakeeping generally promotes safety in extreme weather and has the additional advantage of allowing a full range of operations over a wider range of ship speeds. The ability to launch weapons in heavy weather is an obvious offensive advantage, and having the ability to do so for defensive purposes clearly increases the potential for survival against enemy attack from the air or from submarines. The seakeeping characteristics of a ship can be altered drastically through hull form shaping. Modern computer technology, coupled with advanced CFD algorithms, makes the assessment of hull form optimization possible. Hull forms capable of reasonably high speeds can be developed that minimize the downside impacts of high fuel consumption, poor seakeeping, large wake signatures, or the application of sophisticated systems historically associated with surface effect ships.

Affordability. Flat panels associated with improved radar signature have the compounding advantage of reduced construction costs. Standard shapes allow increased utilization of automated processes. The shape of the hull can have a significant positive effect on maintenance costs as a result of improved corrosion resistance.

Through hull shaping, drag of the body through the water can be reduced in comparison with conventional monohulls. This can lead to both acquisition and life-cycle cost savings associated with the propulsion system and fuel use. Over the life of the ship, even a small reduction in fuel consumption can translate into many millions of dollars in savings for a class of ships. Reduction in drag may be directly associated with reduced powering requirements, which could result in a smaller power plant for a given size ship. Smaller propulsion plants have the inherent benefit of being less costly to procure, and a smaller propulsion plant may provide flexibility in arrangements that benefit other attributes as well.

Operational Availability. Increased speed, seakeeping, and endurance all serve to increase the time available for operations.

Flow Control

Objective

To reduce wake and acoustic signatures while simultaneously reducing vehicle drag and hence power required, or fuel consumed, for a given speed.

Enabling Technologies

Boundary layer control, transition and turbulence control via electromagnetic force application, and other active drag reduction techniques have the potential to enable a significant improvement in drag for both surface and undersea vessels, but the phenomenology is not well understood and, in some cases, not consistently repeatable (in the case of electromagnetic turbulence control, for example). These represent higher-risk, longer-term approaches. Integrated hull/propulsion design, shaping, circulation control, and intelligent vortex generators and strakes are examples of flow control technologies currently under active investigation, but are anticipated to have a more limited (although more certain) payoff. In many cases, the individual efforts may be used in some combination to provide an integrated system design or configuration improvement.

Several technical approaches have been identified to reduce hull drag through reduction of turbulent skin friction: introduction of foreign substances, geometrical modification, controlled suction, electromagnetic force control, and synergism. Polymers and other additives have already been developed, and some of them are available commercially, but additional research is required into methods

for introducing polymers into the boundary layer and for recovering and recycling the additives, thus reducing the space, weight, and cost impact of flow control additives. Additional work on geometrical modifications, such as riblets, large eddy breakup devices, vortex control devices, and convex surfaces may prove fruitful, but examining combinations of these and others (i.e., synergism) may offer the best potential in this area. Another technique, known to work in principal, is microbubble drag reduction, but the challenge of keeping the bubbles below the surface may be insurmountable. This is also an example of an approach that is embryonic in nature and that should be explored at a modest level.

The application of selective boundary-layer suction and other active flow control measures via interactive control loops may show promise in reducing skin friction. Recent developments in the control of chaotic systems and in microfabrication technology provide opportunities for practical implementation of the required large arrays of inexpensive, programmable sensor or actuator chips (microelectromechanical systems or devices) embedded on the surface. These technologies, and the potential systems they may enable, are applicable to surface vessels, submarines, and aircraft.

It appears that the work thus far on boundary layer control using the controlled application of electromagnetic forces has some promise at relatively low Reynolds numbers. The practicality of this approach requires further study.

Benefits

Flow control offers the potential to reduce acoustic and wake signatures, while at the same time reducing drag. Clearly this area merits continued investigation and research since there exist significant potential benefits if the technological challenges can be overcome.

Modular Design

Objective

Future system architectures enable concepts of modular design to be reconsidered in order to achieve both flexibility in upgrading existing combat systems or in installing new systems over the life of a naval ship and a significant reduction in building time and cost.

Enabling Technology

The architecture of future technologies such as CLIDCS, integrated power systems, open architecture networked combat systems, PEBBs, and multifunctional antennas warrants and enables addressing modularity in ship design and construction. Modularity and standardization in future ship design can be extrapo-

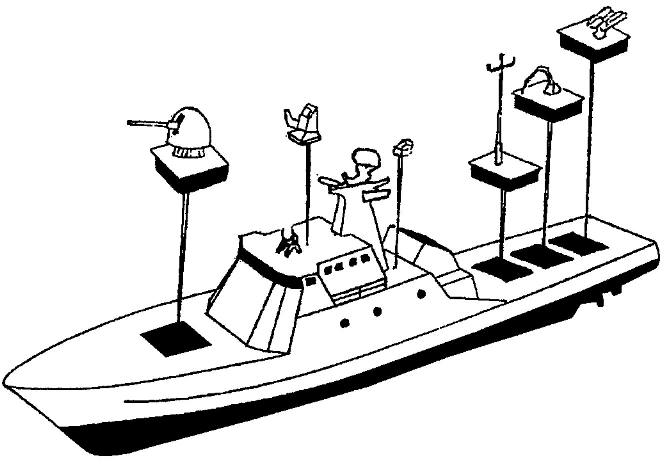


FIGURE 2.2 Danish Navy's Standard Flex 300 design. SOURCE: Jack Guilfoyle, Chris McKesson, Mark Oakes, Robert Scott, Steve Cohen, and Mark Hoggard, "Patrol Craft Requirements and Technology for the Next Century," p. 6-15 in *Symposium on Naval Ship Design for Setting Course for the 21st Century*, Society of Naval Architects and Marine Engineers, Jersey City, N.J.

lated from a program in modularity and standards started in the early 1980s, called the Ship Systems Engineering Standards Program. The concept was to develop interface standards that would permit a wide variety of systems through the easy interchange of modules anytime in the service life of the ship. Standards were developed for the then current vertical launch system, but the program was terminated before additional standards for electronics and machinery were developed.

A limiting factor is the current hard-wiring of systems that are customized for the particular sensors, consoles, computers, and launchers of a specific weapon system. Networking technology will enable the designer to replace the hard-wired system with data buses and standard interfaces that will carry all of the information used by the combat system. These are similar in principle to electric power cables in that power cabling is not predicated on the details of the equipment served. Thus, as long as the data bus has sufficient capacity and standardized interfaces, changes in combat system units should not require rewiring. Moreover, with an open architecture data bus system, important combat system or combat system role changes may be easily implemented as technology advances. If all computers and consoles have access to all data in the combat system, then any one computer or console can be defined to perform any required role. Alternatively, multiple functions, including those outside the combat system, can be monitored or controlled by a single computer and/or console.

The data bus concept can be further extended. Currently, it is usual to distinguish between combat systems and systems such as propulsion, steering,

and damage control. The Navy is beginning to apply data buses to the latter functions. It is conceivable that the boundary between combat and ship systems will become blurred and that a common bus will serve all functions, as well as integrated power systems.

Some years ago the Royal Danish Navy could not replace all of the types of ships it was then operating. Yet it could not abandon roles such as prehostilities surveillance, mine laying, missile attack, torpedo attack, and mine countermeasures. The technologies of data buses and general-purpose computers suggested a solution. A 300-ton corvette, StanFlex 300, shown in Figure 2.2, was designed with containerized weapons and in some cases sensors. Each could plug into the combat system data bus, which also ran through the ship's combat information center (CIC). Each CIC computer and console had its role defined entirely by software, so that it could shift roles easily. In theory, StanFlex 300 can change all of its combat system in 24 hours or less simply by replacing containers and software.

Blohm and Voss (B&V) has been containerizing weapons and other ship components for a number of years. The flexibility of its corvette and frigate designs accommodates the desires of several navies for different combat systems. In 1991, B&V delivered its first frigate with a data bus replacing conventional point-to-point wiring for weapon and electronic systems. This ship was constructed in 32 months. B&V claims that modularization reduced the time from contract award to commissioning from about 72 to 48 months. Attendant with this decreased construction time, however, is an increase in the quantity of connections at the module interfaces and in the complexity of the ship's service systems (air conditioning plants, fire pumps, and so forth) and the ship's structure.

Benefit

Experience to date indicates that designing for flexibility through modularity not only facilitates making changes during the service life of a ship, but also could make ships easier and less costly to construct.

Environmental Control

Objective

To comply with increasing restrictions placed on ship discharge by the international community (e.g., MARPOL Annex V[2]), U.S. maritime organizations are actively seeking to develop technological solutions for the treatment of shipboard

[2] International Maritime Organization Annex V of the *International Convention for the Prevention of Pollution of Ships* (1973) and its 1978 Protocol are known together as MARPOL Annex V.

waste. The difficulties in implementing waste treatment systems on board existing military ships have to do with the volume of waste generated during long military missions. Future shipboard waste treatment systems could consist of an array of separate systems for specific classes of waste, or there could be a single, large-scale waste treatment system that potentially would handle nearly all types of waste streams generated on board naval vessels. The Navy's objective is to develop and field systems that properly treat shipboard waste without hampering a vessel's fundamental military mission, whether during peacetime or war, and minimize this impact on the limited space and power available on board.

Some of the more recent enabling technologies that may be applied here are described below. Other more mature technologies (e.g., plastics processors, pulpers or shredders, and liquid filtration systems) are currently at the implementation stage and are not discussed further.

Enabling Technologies

Supercritical Water Oxidation

Supercritical water oxidation (SCWO) for the destruction of concentrated liquids is a process by which oxidation of waste species takes place in H_2O at very high temperatures and pressures, well beyond the critical point. With residence times of the order of seconds to minutes, SCWO can produce very high destruction rates in a relatively clean, easy-to-control system. Yet it is highly energy intensive, whereas available systems tend to be large, heavy, and relatively expensive.

Advanced Shipboard Incineration Systems

On-board incineration could be an attractive waste alternative from a technological point of view. In addition to providing a significant reduction in waste volume, it is often possible to recover a substantial amount of energy (heat) and material (e.g., acids) through incineration. Nevertheless, as a result of public opposition to the notion of incineration systems, only a small fraction (<5 percent) of combustible waste has historically been treated by incineration on land and the technology has received mixed support in Navy circles. The fact that the few existing on-board incineration systems are extremely old (1940s technology) and inefficient does not help improve this perception.

Shipboard incineration systems could take the form of comprehensive waste treatment systems, such as fixed hearth-refractory box or rotary kiln, which are capable of incinerating a wide variety of solid or liquid waste. Alternately, specialized incineration systems could be used on board to treat specific waste streams, such as sewage concentrate, oily waste, and/or food and paper slurries. Advanced incineration systems based on aerospace propulsion devices, some of which are

being examined through Navy ship environmental R&D program studies, have demonstrated extremely high destruction rates compared with conventional incinerators and should be examined further for future implementation. Thermal insulation and shielding noise control, as well as operator training and expertise, are essential issues for the development of on-board incineration systems.

Plasma Arc Pyrolysis

Plasma arc pyrolysis is an ultrahigh-temperature process that can be used very effectively to destroy both hazardous and nonhazardous wastes in the absence of oxygen. In this process, a direct-current (dc) power source is required to form an electrically discharged plasma arc, which can attain temperatures as high as 15,000°C. Solid waste as well as liquids and slurries can be fed into the arc jet or into the molten slag formed by the plasma arc, whose temperature can exceed 2,000°C. The high temperatures attained in the plasma and molten slag are very effective in destroying waste, yet the combustible gas product usually is burned in an afterburner, and as such, the system can be classified officially by the Environmental Protection Agency as an incinerator, with its associated negative political connotations.

Plasma arc pyrolysis has many potential advantages for waste treatment in general. The slag formed after waste pyrolysis is inert and of relatively low volume; it can be extracted readily from the system. There is also little or no ash discharge, and the gaseous discharge from the process can be passed easily through an afterburner and/or air pollution control equipment such as a venture scrubber. Certain disadvantages, however, may outweigh the advantages. Current plasma arc systems are very large and viewed by some as impractical, given the size constraints on Navy vessels, even on aircraft carriers. Further, a large dc power source is required to create the plasma (500 kW to 1 MW value), in addition to concerns about the IR and electromagnetic (EM) signature associated with the device. Finally, the buildup of slag on the liners of the pyrolysis chamber (usually from glass) can be excessive, requiring periodic removal, but liner replacement is common to most thermal destruction systems.

An alternative plasma-based system that may be suitable for shipboard waste treatment is the silent discharge or nonthermal plasma process. This process is based on the formation of free radicals in a nonequilibrium plasma that is created by electrical discharges from electrodes covered with a dielectric material. This approach can have advantages over thermal plasma systems because the nonthermal plasma component of the system is mostly silent, and waste is destroyed at ambient temperatures. Its power requirements are typically lower than those of thermal plasma systems for similar volumes of waste processed.

Benefits

There are a number of advanced waste treatment technologies that could be exploited, even in the near future, to solve shipboard waste management problems.

Since fuel for the ship's propulsion plant is already part of the existing shipboard system, waste treatment systems utilizing this same fuel for operation (e.g., incineration) may be integrated more easily into the ship. Highly energy-intensive devices such as the plasma arc pyrolysis system, however, could necessitate an external generator, introducing additional complexities to the ship system.

If one overall treatment technology for all waste classes is implemented on a ship, very reliable backup systems would be required. If significant "downtime" occurs for a single large system, whether due to routine maintenance or system upset, nearly every waste stream generated on board could be affected and would have to be stored, at least temporarily, until the problem was solved. Alternately, if multiple, diverse technologies are used, more complex failure pathways might occur, but they would be much less likely to affect all waste streams at once. This observation indicates that specialized treatment systems could work quite well within the system that makes up a military vessel and should be explored by the Navy.

Aircraft Catapults

Objective

Replace the steam catapult in order to gain flexibility in the choice of main propulsion plants and achieve significant savings in the space and weight of the catapult system.

Enabling Technology

Currently, research is being conducted on two alternative catapult systems: an electromagnetic system and one powered by an internal combustion engine. Such catapults must be compatible with the launch thrust requirements for current as well as potential new aircraft.

Benefit

The introduction of an alternative to the steam catapult on new aircraft carrier designs would eliminate the dependence of the catapult system on steam from the main power plant. This offers the following options to the platform designer:

TABLE 2.2 Surface Ship Technologies

	Minimal Manning Through Automation	Integrated Electric Power and Propulsion Systems	Signature Reduction	Modular Design	Environmental Control	Aircraft Catapults
Platforms						
Carrier	X	X	X	X	X	X
Surface warfare combatant	X	X	X	X	X	
Arsenal ship	X	X	X	X	X	
Amphibious ships	X	X	X	X	X	
Major improvements						
Reduced life-cycle costs	X	X		X	X	X
Reduced development time			X		X	X
Reduced logistic support	X	X				
Increased range		X			X	
Increased survivability	X	X	X			
Increased effectiveness	X	X	X		X	X

1. A wider choice of main power plant (e.g., diesel, gas turbine, high-power-density nuclear), and
2. Elimination of the weight (approximately 440 tons in a large carrier) of the piping for the steam supply.

CONCLUSIONS AND RECOMMENDATIONS

Summary of Applications

Table 2.2 summarizes the applications of the foregoing technology thrusts, in terms both of the platforms that will benefit from these developments and breakthroughs and of major improvements in performance and affordability factors.

Payoff

Successful pursuit of these technologies offers the potential for a streamlined, affordable, and effective fleet of surface ships. The smaller crew sizes and increased automation will facilitate focusing ship operations on the primary military missions. The technologies discussed offer potentially unprecedented levels of platform commonality with attendant benefits in training, logistics, and reduced life-cycle cost. Integrated electric power and propulsion systems will provide great opportunity for advances in standardization.

Composite development will be a key part of signature reduction efforts, along with advanced hull forms and flow control. In addition, flow control, if successfully pursued, will offer many benefits from increased range for a given speed to smaller ships for a given endurance. Modular design will permit increased flexibility in fielding new weapons and other warfighting improvements as they emerge. The environmental effort has a long-term benefit for humanity as well as putting the Navy on a standard course. Finally, aircraft catapult work is needed to open new possibilities in the design of aircraft carriers. The Navy-Marine Corps team, by emphasizing certain thrusts, can make major strides toward creating a winning force for 2035 with only a modest impact on current programs.

Although all of the technologies recommended by the panel for application to surface platforms are worth pursuing, three recommendations stand out in terms of potential payoff (both near term and far term):

1. Automation to reduce manning will enable a significant realization of life-cycle cost savings.
2. Integrated electric power and propulsion systems offer improved power density, greater ship arrangement flexibility to maximize payload, and improved affordability.

3. Composite materials offer opportunities for heterogeneous fabrication that supports new possibilities for signature reduction.

Work should move forward in all three areas now. All offer clear opportunities in the relatively near term, as well as promise for increased benefits in the longer term as the development of resources and increased attention drive the technologies toward maturity.

3

Naval Air Platform Technology

OVERVIEW OF FUTURE NAVAL AIR TECHNOLOGY

Initial Observations

In reviewing relevant technologies and formulating its findings, the panel took special note of significant trends in employment concepts for air platforms:

- Increased emphasis on long-range, precision weapons, launched from both aircraft and surface vessels;
- Expanded consideration of off-board sensing and targeting; and
- Growing concerns about employing manned aircraft in combat operations over land, particularly during daylight hours.

It will be important to strike a balance among tactical air platforms, sophisticated weapons, and off-board sensors in order to provide the most cost-effective approach for the future. Acknowledging calls for increased emphasis on unmanned aerial vehicles (UAVs) for a variety of support and lethal missions, the panel believes that the argument over manned and unmanned aircraft—although an important one—is not the real watershed decision for 21st-century naval aviation. The cardinal aircraft issue for future decisionmakers is that of tactical aviation (Navy, Marine Corps, Air Force) versus standoff weapons, long-range bombers, and ship or shore basing. This issue is not addressed here, but nevertheless must underlie any consideration of the future character of naval aviation.

Vision of Naval Air Platforms for 2035

A More Vertical Force

Naval aviation, both afloat and ashore, is likely to become a more vertical force in the future. There will be increased reliance on air vehicles, both manned and unmanned, with short takeoff and vertical landing (STOVL), vertical takeoff and landing (VTOL), and short takeoff and landing (STOL) characteristics that have excellent payload, range, and low-signature capabilities. Takeoff and landing footprints will be much less than today's conventional takeoff and landing aircraft, thereby opening up design space for future aircraft carrier development.

Unmanned Aircraft

Naval aviation will employ UAVs for a variety of missions, beginning with reconnaissance, surveillance, and targeting, and later expanding to include such familiar aircraft carrier (CV) support tasks as tanking, electronic warfare (EW), antisubmarine warfare (ASW), and airborne early warning (AEW). Some of these unmanned aircraft will fly from aviation ships and surface combatants, whereas others, some possibly operated by the Air Force, may be based ashore at great distances from the supported battle group or expeditionary task force. As UAVs become more reliable and gain operational acceptance, unmanned tactical aircraft will be employed for selected lethal purposes, both air-to-air and ground attack. The panel believes that the introduction of unmanned tactical aircraft as substitutes for today's fighter and attack planes will be a slow "fly-before-buy" process, and that a place will remain in the naval aviation arsenal for piloted tactical aircraft for many years to come.

Aerial Trucks

The introduction of subsonic, stealthy-when-required, aerial trucks is seen as a major positive development for the future. These aircraft—manned and unmanned—and employing STOVL, VTOL, and in many instances, STOL capabilities could constitute the backbone of naval aviation for the missions cited above. These workhorses would be mission configured using modular packages that could be changed in a reasonable time aboard ship and at advanced shore bases.

Broadened Aircraft Basing Options

Carrier Size

Because of the trend toward a more vertical force of aircraft with attendant reduced demands for takeoff and landing deck space, the spectrum of acceptable

aircraft carrier sizes and configurations is broadened considerably. Seakeeping characteristics of aviation ships are also less constraining on STOVL and VTOL aircraft—and to some extent STOL—a fact that contributes to lowering the ship tonnage threshold below that for which safe air operations are now viable.

Vertical aircraft also contribute to cost-effectiveness in other important ways—in sortie generation and the attendant quantity of munitions delivered on target. A ship with a vertical air wing can carry more such aircraft than conventional takeoff and landing (CTOL) aircraft and, for short to medium ranges, STOVLs and VTOLs can cycle at a greater rate. This adds up to more sorties and more ordnance delivered in a given period of time.

Distribution of Air Assets

The panel sees aircraft, some with considerable combat capability, being distributed more widely among ships of the fleet. Improved system reliabilities and the greater prevalence of vertical aircraft will make such distribution feasible in many instances, at least on a temporary basis, as dictated by the tactical situation.

Flexible Carrier Deck Loads

Although commanders have always been able to tailor the mix of aircraft types in a carrier air wing, force options of unusual flexibility will be open to the Navy in 2035 if the requisite enabling technologies are developed and exploited. For example, support aircraft functions—tanking, EW, ASW, AEW—could be provided by shore-based air platforms, the majority unmanned, that operate from airfields perhaps thousands of miles away and remain on station in support of battle groups for periods of two days or more. A CV in this instance could function as an all-fighter attack base and munitions magazine, greatly increasing the striking power of the all-fighter battle group. Alternatively, under a different tactical scenario, the carrier could serve principally as a support and/or reconnaissance and surveillance base, operating troop lift and logistics aircraft as well as special mission planes that provide reconnaissance and targeting support for expeditionary forces ashore and control long-range missiles launched by bombers and surface ships.

TECHNOLOGY DEVELOPMENT PLAN

The panel believes that a plan to develop future technologies for naval aviation should embrace the following elements:

1. Make maximum use of technological advances in the commercial aviation sector, as well as advances developed by the Air Force, Army, and NASA.

Interservice cooperation has improved over the years, and the Navy has benefited considerably from R&D conducted by NASA and by the other military services. This policy should be continued and, indeed, information exchange and sharing, including joint technology planning and development, should be enhanced whenever possible. Navy R&D planners should seek to maintain and improve strong working relationships with NASA R&D planners to encourage recognition of Navy needs within NASA and to maximize the utilization of technology available from the relevant NASA programs.

2. Continue the general course of Navy-funded R&D as outlined in current plans, but also maintain a healthy watch for the occasional nonessential pet projects that can creep in and soak up resources. By maintaining the current path, the Navy will be assured of having technologies in hand that facilitate evolutionary development of current air platforms should this course of action be chosen in the future; however, the panel believes that this course alone is inadequate to met the challenge of the future.

3. Implement new, focused R&D thrusts in the following air platform technology areas, building on current progress within the Navy and in joint efforts with the Air Force, the Army, and NASA:

- Aerodynamics,
- Structures,
- Propulsion,
- Flight and mission control,
- Signature reduction, and
- Design and manufacturing processes.

Technology Toolbox/Buffet Line

The panel suggests that the Navy view its future R&D challenge as one of developing tools, including borrowing, wherever possible, those funded and developed by civil aviation, the Air Force, and the Army. These tools would then be placed in a toolbox ready to be used or presented on a technology buffet line. Thus, when the time comes to develop a tactical aircraft after the joint strike fighter (JSF) or a follow-on support aircraft, the Navy will have the option to pursue either a traditional evolutionary path or one that exploits the enabling technologies identified in this report, with the attendant new platform concepts identified by the panel.

Key Enabling Technologies

The panel identified 12 key enabling technologies (Table 3.1) that are uniquely applicable to naval aviation platforms and may be underemphasized within the Navy Department's current R&D portfolio.

Investment by the Navy Department in the 12 enabling technologies that

TABLE 3.1 Key Enabling Technologies

Technology Focus Area	Key Enabling Technology
Aerodynamics	Laminar flow control High-lift aerodynamics
Structures	Lightweight, high-strength composites
Propulsion	Core engine performance Variable cycle engine Adapting large-engine technology to small engines
Flight and mission control	Integrated flight and propulsion control High-capacity, long-range data links
Signature reduction	RF signature reduction IR signature reduction
Design and manufacturing processes	Dynamic electronic prototyping Reduced-cost, low-rate production

capitalize on and leverage the established aerospace R&D path could broaden the air platform and aircraft basing options for naval forces in the year 2035. By exploiting these enablers, and as success is demonstrated, those officials who set operational requirements and formulate acquisition programs will be afforded increased flexibility in fashioning designs of aircraft and aviation ships to meet future needs of the Navy and Marine Corps. These needs will embrace a wide mission spectrum in an era of rapid change in information technologies, increased reliance on precision-guided munitions, and demands for lower cost and possibly fewer aircraft and base ships.

The panel believes that developing and deploying more cost-efficient air platforms and supporting sea bases are feasible and necessary goals. These aircraft and aviation ships will confer warfighting benefits that will be unattainable if R&D proceeds solely along the traditional path, wherein each aviation community (i.e., fighters, strike, reconnaissance, surveillance, ASW, EW, and troop lift) seeks a successor model possessing increased performance.

The enabling technologies and their impact on future air platform designs are discussed in the context of the technology focus areas for future naval air platforms described below.

Integrated High-Performance Turbine Engine Technology

The Defense Department's very successful Integrated High-Performance Turbine Engine Technology (IHPTET) program, which was initiated in 1988 and will proceed in phases until 2003, constitutes an excellent model for a technology

development program. Its success is attributable to four crucial elements: (1) the subject is seen as important; (2) clearly defined technical and schedule goals are specified; (3) the effort is a government and industry partnership; and (4) stable funding profiles are established and adhered to. The panel believes very strongly that IHPTET should serve as the model for air platform technology development.

TECHNOLOGY FOCUS AREAS

Aerodynamics

Laminar Flow Control

The most significant air platform performance parameter for mission capability is range and, alternatively, endurance—both of which are major functions of cruise efficiency. From an aerodynamic perspective, this relates to low cruise drag.

Current Situation and Constraints

Many factors can dominate cruise drag: shape (or fineness), wing platform and aspect ratio, airfoil design, size, gaps and protuberances, surface roughness, engine inlets and nozzles, and control or trim surfaces. It is well known that a particular design to accomplish a specific mission is a compromise among mission elements such as maneuver performance, takeoff and landing performance (especially for sea-based air), and cruise performance. In addition, for fighter, attack, and reconnaissance aircraft, external stores are often used to increase payload and/or range at the expense of cruise drag.

Many advances in technology have enabled refinement of aerodynamic shape for the basic platform as well as the external pylons and stores and their integration. Flight control technology has led to reductions in trim drag. Sophisticated analytical tools and design codes have facilitated optimum wing designs and inlet and nozzle integration based on dominant elements of the mission profile. As analytical tools continue to be refined, so does the understanding of flow phenomena, flow interactions, and drag. Computer-aided design tools facilitate moldline definition (and build) with unprecedented fidelity. New structural design techniques and composite structure process development are enablers for high-aspect-ratio wings to extend both the altitude and the endurance envelopes for special-purpose aircraft. These kinds of improvements are addressed almost daily and can be classified as business as usual from an aerodynamic perspective. There is, however, one particular aerodynamic technology with tremendous potential to improve cruise performance that is not business as usual. This is the area of laminar flow control.

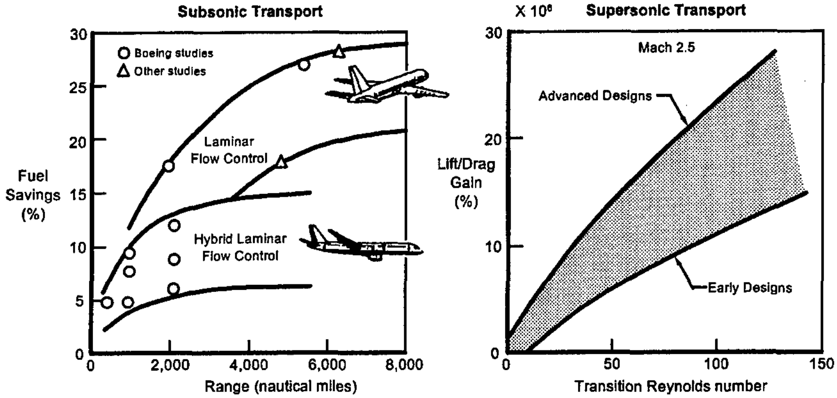


FIGURE 3.1 Potential gains from laminar flow control. SOURCE: NASA Langley Research Center Web site at http://128.155.35.117/LFC_www/LFC.html.

Key Enabling Technology

Laminar flow control is a technique to control the boundary layer or the airflow closest to the skin. By maintaining laminar flow in the boundary layer and controlling the transition to turbulent flow, drag can be reduced significantly, buffet onset and flow separation can be delayed, and the flight envelope can be extended efficiently. Usually this is best accomplished by venting or bleeding the boundary layer via suction through a porous skin. An alternate technique is pulse blowing at frequencies tailored to unstable fluctuations in the location of boundary-layer transition. Interaction of the secondary flow with the primary airflow stabilizes the boundary layer and maintains laminar flow. Yet another technique, primarily useful at low Reynolds numbers, is to tailor the airfoil shape to maintain laminar flow. Figure 3.1, provided by NASA and based on work conducted at the NASA Langley Research Center and the Boeing Company, illustrates significant potential gains from the application of laminar flow control to both subsonic and supersonic flight. Fuel savings of the order of 10 to 20 percent can be realized for subsonic narrow-body transports, whereas fuel savings in excess of 20 percent are projected for wide-body transports with ranges greater than 4,000 nautical miles. Alternatively, research studies on high-speed flight indicate that supersonic cruise lift-to-drag ratios can be increased on the order of 10 percent at speeds of Mach 2.5, depending on the transition Reynolds number.

The feasibility of these concepts has been demonstrated in both laboratory and flight research. For example, Figure 3.2 depicts one of the flight test vehicles, an F-16XL at the NASA Dryden Flight Research Center, that has been modified to conduct supersonic laminar flow control research. Close inspection of the port wing reveals the test panels in the enlarged glove area. Other flight

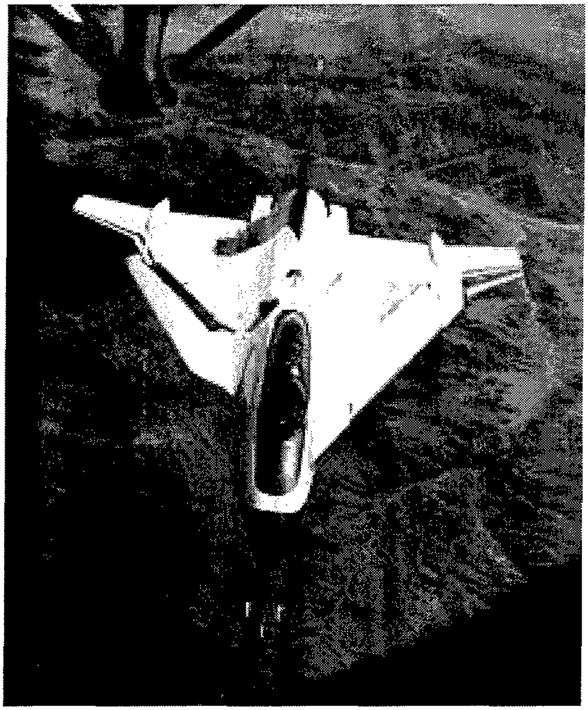


FIGURE 3.2 NASA laminar flow flight test vehicle at the Dryden Flight Research Center. SOURCE: NASA Langley Research Center Web site at http://128.155.35.117/LFC_www/LFC.html.

test research has been conducted using a Boeing 757 for investigating laminar flow control in the subsonic regime.

Recent accomplishments have been facilitated by a greater understanding of the flow phenomenology via development of CFD codes and breakthroughs in processing technology. Outstanding analytical and empirical correlation has been demonstrated for the F/A-18. Physical implementation of laminar flow control technology requires exacting external moldline (skin) definition, fabrication, preparation (hole location and size), and operation (vent flow control). As noted above, computer-aided design and manufacturing (CADAM) is a significant enabler in attaining the necessary fidelity for the moldline surface and for vent (port) locations. Control of the secondary flow through these vent holes is now feasible and manageable using advanced digital electronic controls and modern processing capabilities. Specific matching of the secondary flow management to the moldline shape and flight condition remains a challenge. These elements should be areas of continued Navy focus.

However, much work remains to enable full integration into aircraft design.

Issues range from those associated with product definition in the laboratory to those associated with operational employment in the fleet. Analytical and experimental work to refine the moldline definition, vent hole distribution, and flow control based on specific design applications (fighter, support, surveillance) and platforms, wind tunnel validation of numerical codes, and the definition of robust scaling laws for naval air vehicle applications are all required before laminar flow technology is mature enough for full implementation. Operational issues include maintaining adequate bleed port operation (size and number of ports) and vent control, given the potential for surface contamination by rain, dirt, or salt spray. A range of solutions should be examined, including surface treatment, redundancy management for the ports, characterization of failure modes and effects, and maintenance and repair concepts. These efforts should not be conducted at the expense of pressing for continued progress in product definition, manufacturing, or flow control quality. Efforts should be coordinated with applicable work in contributing materials, structures, and manufacturing technology program elements.

Other Contributing Technologies

There is a distinct interaction between laminar flow control technology and several other technologies described in this report. Many of the wind tunnel and CFD tools used in laminar flow control R&D are applicable to high-lift aerodynamics issues as well. Large, complex unitized composite structures play a role in moldline and surface fidelity, and new processes enable very-high-aspect wing development. These have to be tied together from a Navy applications perspective for common support aircraft and UAVs. The variable cycle engine enables mission matching and may be valuable to offset traditional vent and bleed losses, depending on the specific breadth of Navy platforms and tailored mission applications. Integrated flight and propulsion control facilitates attainment of efficient trim conditions and integration of vent port flow control as a function of flight or maneuver envelope for all vehicles. Techniques to provide radio-frequency (RF) signature reduction will also reduce gaps and protuberances and should be considered when implementing laminar flow control methods in applications where stealth may be an issue, particularly for new-design fighter or attack aircraft and UAV applications. Dynamic electronic prototyping is an essential tool for evaluating particular designs, as are many of the tools used to facilitate reduced-cost, low-rate production.

Potential Payoffs for Future Air Platforms

Improved aerodynamic cruise performance has a first-order, fundamental effect on all aircraft design. Reduced drag and improved cruise efficiency provide design options to (1) increase endurance and operational altitudes for UAVs or

surveillance aircraft; (2) increase payload or range for the same size and weight platform in remaining naval air applications; or alternatively, (3) reduce platform size and weight with increased efficiency. All of this equates to decreased acquisition (size) and operational costs (fuel) for the life cycle of the vehicle.

Recommendations

To realize the potential offered by laminar flow control, several technology areas should be pursued to round out the fundamental understanding and provide for operational applications and transition:

- The Navy aerotechnology base should provide validated product definition and analysis tools, including shape, location, flow port patterns, and flow control. The Navy materials technology base should be tasked to provide coatings to prevent contamination and blockage of the secondary flow ports.
- Elements of the Naval Air Warfare Center (NAWC) and the Naval Air Systems Command (NAVAIR) should explore specific vehicle and mission applications. Research and development efforts on an integrated systems basis should provided parameters for control system development, critical operational (and failure) modes, and repair and maintenance techniques. These integrated efforts should extend to operational control and integration with variable cycle engine technology and should draw on advanced composite structures technology for characterization of new classes of air vehicles such as common support aircraft or surveillance UAVs.

High-lift Aerodynamics

One of the fundamental issues in carrier aviation is the ability to generate high lift at low speeds for takeoff (catapult) and landing (trap), particularly at maximum payload and bring-back weights typical of fighter or attack aircraft and fleet support carrier aviation. From an aviation safety perspective, lower approach speeds are desirable. Level 1 handling qualities at any approach speed are mandatory.

Current Situation and Constraints

Providing good high-lift capability for shipboard operation is a demanding task, particularly for modern supersonic jet aircraft. High-lift requirements for catapult and for approach or arrestment are different. Launch requirements typically are accompanied by lift and acceleration demands at heavy gross weights. For arrestment, maximum bring-back loads are important, but the requirements are to maintain a steady approach angle and altitude at low speeds through to arrestment. These high-lift requirements often introduce constraints and aircraft

design considerations that conflict with other mission design requirements. In particular, a wing optimized for high-speed flight should be very thin and highly swept, with little camber and twist. Low-speed aerodynamic efficiency, on the other hand, requires a relatively thick unswept wing, with high camber at the leading edge, preferably for full span. Many complex solutions have evolved over the years, including variable incidence (with respect to the fuselage) nose strut extension for catapult such as that used on the F-8; variable sweep as with the F-14; and numerous flap, slat, and slot arrangements on the wing's leading and trailing edges—some of them augmented by a complex active boundary layer control and blowing systems (e.g., the F-4). Increased flap area or deflection also has an effect on wing pylon and external stores integration (e.g., F/A-18) due to the physical clearances required for full flap conditions. Leading and trailing edge flaps are typically complex, have bulky drive systems creating external bumps, add significant weight to the airplane, and are a high-maintenance item. Often, developing excellent handling qualities for low-speed flight conditions is an exacting job because of the significant change in lift distribution and lift as a function of both airspeed and angle of attack. A fundamental issue is the ability to characterize the high-lift flow field, including repeatable flow through flap vents and slots, especially as it is affected by flow from the main wing or flow shed from the fuselage. Analytical tools for this complex flow field are not fully developed, yet this condition is fundamental to effective and safe CV operations. Researchers are gaining a greater understanding and appreciation of shed vortices from complex fuselage shapes, chines, or windscreen and canopy every day.

Achieving a better understanding of high-lift aerodynamics and flow field interactions with and through deployed surfaces can provide a major breakthrough for simplification of wing design while maintaining repeatable low-speed handling qualities, high bring-back weights, and safe boarding rates. It is critical to maintain nonseparated flow over the deployed flap system. This requires further aerodynamic code development and an intense empirical interaction (i.e., wind tunnel test) for reduction to design practice. Figure 3.3 illustrates some of the outstanding problems that have yet to be solved.

Key Enabling Technology

Significant experimental work has been conducted in conjunction with the F/A-18 E/F program. Computer-aided design and analysis has enabled major progress for characterization of the high-lift flow field. An operable Reynolds-averaged Navier-Stokes turbulence model (both two dimensional and three dimensional) has been developed and validated to a large extent in wind tunnel tests. This has been facilitated by developments in processing capability and the ability to define a single three-dimensional solid geometry analytical and design data base for wing-flap-slot systems. Further, advanced test and flow field measurement techniques, such as a laser Doppler velocimeter, have been integrated

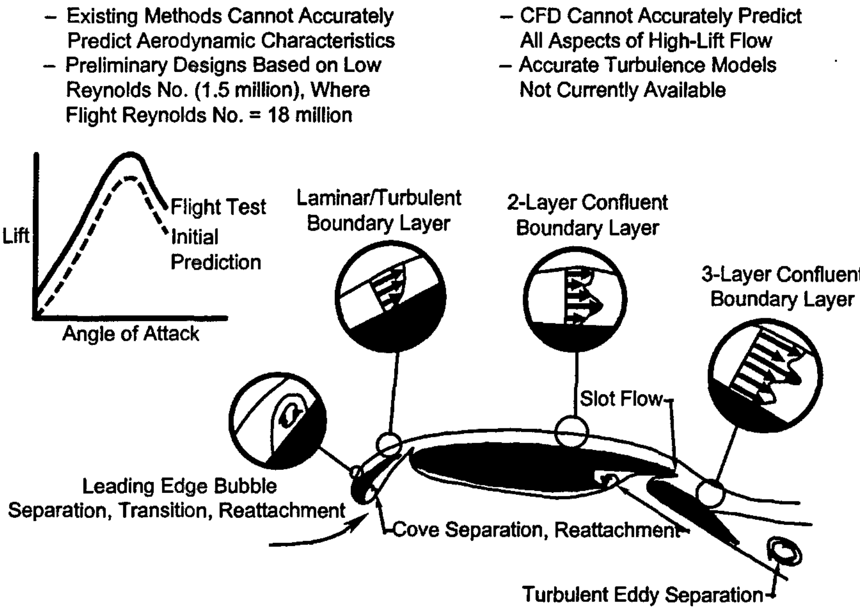


FIGURE 3.3 High-lift system design problems for current and future fighter configurations. SOURCE: Courtesy of McDonnell Douglas Corporation.

into wind tunnel testing using variants of F/A-18 wing system models at NASA Langley and have added immensely to the understanding of the flow phenomenology. So-called smart structures and shape-memory materials may facilitate implementation of an effective and repeatable design.

Many technical challenges remain. Researchers need to gain a fundamental understanding of off-body flow field bubble formation and its prevention. Vortex control research should be conducted to better understand and facilitate flow field control, as well as repeatable gap vent flow control (between flap surfaces and wing), and solid analytical or empirical correlations are yet to be developed into a closed form design process. This requires extended analysis and wind tunnel testing for a variety of wing and wing flap configurations applicable to carrier-based fighter, support, and surveillance UAV aircraft, in the presence of fuselage or other body flow (e.g., pylon landing gear, door shed flow) at full-scale Reynolds numbers and incidence angles typical of approach conditions. These efforts could be undertaken as part of the naval aerotechnology base maturation efforts and for related programs such as the JSF and the common support aircraft (CSA).

Other Contributing Technologies

A distinct interaction exists between this technology and others described in this report. Many of the wind tunnel flow measurement and analysis tools are applicable to aerodynamic cruise performance research. Lightweight, high-strength composites may be used for complex wing-slat-flap system design and development for all carrier-based aircraft. Integrated flight and propulsion control may be used to maintain excellent handling qualities off the catapult and through trap in the high-lift configuration, including automatic flap control. Dynamic electronic prototyping can be a significant benefit for definition of mechanisms and flap motion for implementation of the particular design, as can many of the same techniques used to facilitate reduced-cost, low-rate production.

Potential Payoffs for Air Platforms

Greater (and repeatable) high lift efficiency is a fundamental design parameter for carrier suitability, especially in the power approach condition. The benefits are direct in terms of lift capability (bring-back load) and approach speed for fighter squadron (VF), attack squadron (VA), and CV-based support aircraft. Such capability provides the naval aircraft designer options to balance payload and approach performance with wing high-lift system design complexity, size, weight, and cost. This extends also to greater safety in carrier operations and could facilitate STOL applications for CVs, air-capable platforms, and land-based patrol squadron (VP) aircraft as well. Successful implementation could also alleviate future shipboard catapult and arrestment gear design requirements (soft cat and trap) to provide significant life-cycle cost savings.

Recommendations

The Navy aerotechnology base should provide validated analytical tools for the complex flow fields (including vortex flow surrounding the fuselage and wings) at high-lift carrier approach conditions. This includes research in flow measurement instrumentation, extension of current laser velocimeter techniques, and testing of complex airfoil and wing-body shapes. Further attention has to be given to development of flow control techniques in this environment.

Extension of the technology into practical solutions and vehicle applications by NAWC and NAVAIR is fundamental to the successful transition of the technology to future operations systems such as the CSA, JSF, and beyond. It is appropriate for systems integration efforts to tie this technology to smart structure developments.

Structures

Lightweight, High-strength Composites

Composite structural materials have long held the promise of significant weight reduction for combat aircraft. Nominally, 10 to 15 percent (by weight) of modern tactical aircraft structure is made of composite materials. The AV-8B and AV-8B+ Harrier aircraft contain roughly 26 percent composites by weight, ostensibly to capture the weight savings leverage for tactical VSTOL capability. Unfortunately, composites are still relatively costly, although they are likely to be more affordable with dedicated attention to capturing the inherent benefits of the material in design, fabrication, assembly, and support.

Current Situation and Constraints

In the majority of applications to date, designers have been inhibited by the availability of proven automated fabrication processes and the need for autoclave cure at relatively high temperature and pressure. As a result, many applications consist of material substitution (i.e., composites for aluminum) with the resultant unimaginative structural design concepts referred to simply as black aluminum. Larger flat skins have been used for wing and tail surfaces, although automated tape lay-up processes enabled introduction of significant curvature for the B-2 bomber and for the AV-8B forward fuselage. Much effort has gone into co-curing skin and stiffeners in the autoclave, but both tools and inspection are expensive and defect correction is even more costly. For the most part, fabrication of composite structures is labor intensive and expensive. Adding to cost and quality issues are considerations of material storage at 0°F and limited storage life (pre-cure). Application of specific materials (fiber and resin combinations) is temperature and load dependent, with high-temperature applications requiring special formulations and load applications requiring attention to fiber strength properties and orientation. In fleet operation, special attention must be given to corrosion prevention and to maintenance and repair techniques applicable to the specific materials used.

Attention to affordability has given rise to new design, manufacturing, assembly, and inspection processes. Through the use of advanced finite element codes and computer-aided engineering, designers are able to use the material properties to produce nonconventional, lighter, and less expensive designs. A number of recent composite structure programs including those at Navy ManTech (the Navy's manufacturing technology development program), NASA, and the composite structure programs associated with development of the JSF are addressing new design fabrication and tooling techniques to realize both weight and cost savings. Navy efforts are focused on V-22, F/A-18, and JSF. Navy ManTech efforts are focused through the Great Lakes Composites Consortium and are

making good progress in determining new materials and manufacturing processes.

Certain key characteristics have become apparent across these programs from a technology perspective, most of which relate to the automated production of relatively large unitized structures to deliver the fundamental process quality and reduced numbers of parts, tools, and fasteners.

Key Technology and Enabler: Lightweight, High-strength Composite Structures

Many enablers come into play in this technology. Arguably, it may begin with new high-modulus carbon fibers and new resin systems from the Navy's materials technology base programs, tailored to strength and temperature applications. For stiffened skins, this can include new core material formulations of either foam or honeycomb. Another key is the evolution of design and analysis codes using high-speed processing and facilitated by a single three-dimensional digital solids model for a database to capture feature-based design techniques. This allows the exploitation of material properties for an efficient integrated structural design. These elements are the basis for the newly initiated Advanced Lightweight Affordable Fuselage Structures (ALAFS) program, whose goal is to reduce cost by 30 percent and weight by 20 percent for a major structural element. This structural element will extend from wing-fold to wing-fold and will integrate the fuselage and wing carry-through structure. Figure 3.4 illustrates a

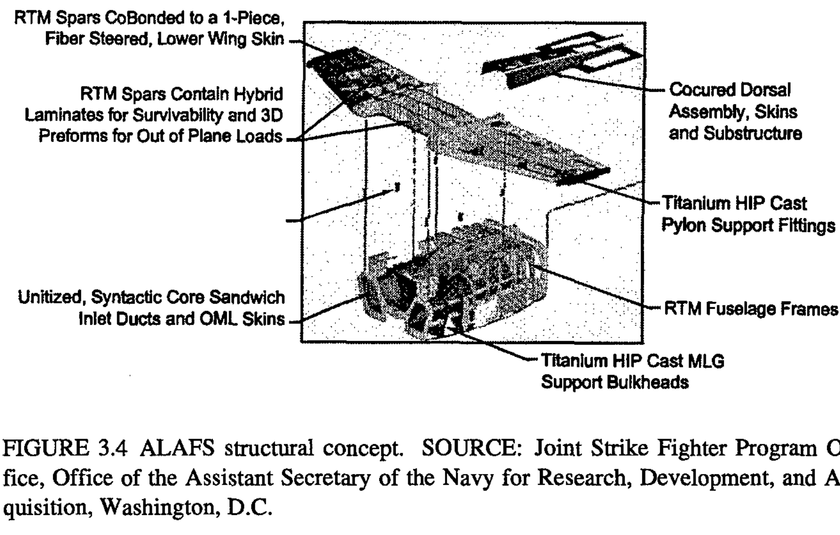


FIGURE 3.4 ALAFS structural concept. SOURCE: Joint Strike Fighter Program Office, Office of the Assistant Secretary of the Navy for Research, Development, and Acquisition, Washington, D.C.

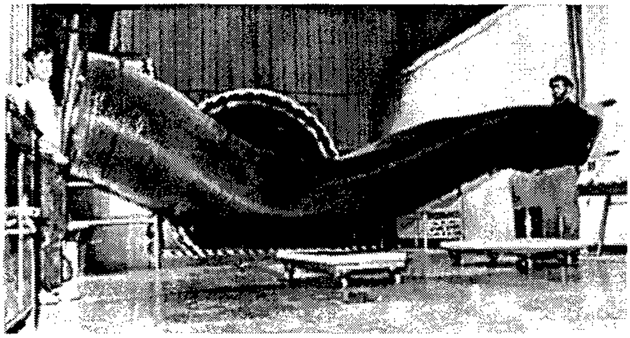


FIGURE 3.5 Fiber-reinforced single-piece inlet duct. SOURCE: Courtesy of McDonnell Douglas Corporation.

concept for a structure for the ALAFS program. The ALAFS structural concept includes titanium hot isostatic press (HIP) cast main landing gear support bulkheads and pylon support fittings, resin transfer molded (RTM) spars and fuselage frames, and unitized syntactic core sandwich inlet ducts and outer moldline skins. The RTM spars are co-bonded to a single-piece fiber steered lower wing skin. The RTM spars contain hybrid laminates for survivability and three-dimensional preforms for out-of-plane loads. The fuselage center section is capped with a co-cured dorsal assembly, including skins and substructure.

Of course, the designs must capture the full benefit of available fabrication and tooling concepts, such as advanced fiber placement, stitched resin film infusion, and arc-sprayed composite autoclave tooling. Such manufacturing processes lend themselves to process control and operator verification, rather than postfabrication inspection. Large unitized structures such as single-piece spars, complex single-piece inlet ducts, and skins (with numerically controlled or placed apertures for doors and other access) have been demonstrated in the laboratory to yield first-time quality, with further cost reduction in assembly. Figure 3.5 shows a fiber-reinforced composite single-piece inlet duct.

For more heavily loaded structures, there have been significant improvements in processes for co-cure reinforcement and bonding techniques. Other developments, taken from outside the aerospace industry, show promise for noncritical structural elements. These include chopped fibers, from short-length random orientation to distributed directionally oriented multiple-length fibers, and resin transfer molding.

Much of the effort described is in the concept analysis, laboratory demonstration, or prototype machine stage. Some of this technology has already been incorporated into products such as the C-17, F/A-18, V-22, and F-22. More advanced elements will be incorporated into the JSF, with potential backfit to the

F/A-18 E/F. A continuing technical challenge remains to define and characterize material properties throughout a wide temperature range and to evolve designs that can exploit existing and new material properties. This challenge should be at the heart of the Navy's material technology base program. Fabrication process development must be continued and expanded via Navy ManTech programs to reduce the touch labor content and to provide built-in quality using advanced automated process control techniques. For the assembly phase, continued effort must also address joining and bonding techniques and reduced-cost tooling, all worthwhile Navy ManTech objectives. Providing the technology in a state of readiness for platform application and use is the expensive R&D proposition, including investment in technology base and machine tools; it requires a long-term stable commitment by NAWC and NAVAIR and a commitment to transition the technology, as in ALAFS. Finally, no development can be considered complete without a substantial companion effort to improve the damage tolerance and fleet reparability of the resulting products. The processes should be an integral part of the navy technology base.

Other Contributing Technologies

There is a distinct interaction between this technology and others described in this volume. In many respects, this technology will enable attainment of the aerodynamic and signature performance goals by providing a high-fidelity, stable external moldline and tailored apertures. Implementation of this technology is enabled by the use of dynamic electronic prototyping and reduced-cost, low-rate production concepts. Electronic prototyping provides a stable design and analysis tool for the products. At the same time, continued development will require the capability both to model the process technology and to diagnose fabrication process parametrics and implementation. Development of reduced-cost, low-rate production methods goes hand-in-hand with successful implementation of this technology.

Potential Payoffs for Air Platforms

Lightweight, high-strength composites have been proven to have a first-order performance payoff (i.e., weight and size for tactical, vertical lift, and high-altitude surveillance UAVs). Attainment of the goals noted here for this technology would provide a needed extension (i.e., reduced acquisition and life-cycle cost for all air platforms). Success with this technology provides leverage for high-aspect-ratio stiffness critical designs (i.e., it facilitates development and introduction of UAVs) and for very weight critical designs (i.e., it facilitates development and introduction of aircraft employing STOVL, STOL, and VTOL concepts). In addition, the technology can be expanded to submarine, surface

vessel, and vehicle applications where balance, corrosion control, or survivability issues may benefit.

Recommendations

- The Navy materials technology base program explained above should continue to define and characterize materials properties through a wide temperature range. Materials should include high-modulus fibers, high-temperature and extended-shelf-life resin systems, and chopped fiber concepts.
- The technology base programs have to be integrated with new fabrication and manufacturing processes to eliminate touch labor and emphasize process control for quality. Companion efforts should include fabrication and assembly tooling, and bonding and joining techniques.
- Additional ManTech program emphasis should be given to integrated design, fabrication, and analysis efforts to provide relatively large unitized structures (reduce the number of parts and fasteners) and employ feature-based design. Both the material technology base and the ManTech programs should focus on damage tolerance design, as well as repair and maintenance techniques.
- NAWC and NAVAIR should continue efforts to explore design applications to transition the technology and to provide enhanced cost and weight performance for future air vehicles such as CSA, JSF, and surveillance UAVs.

Propulsion

Early jet engines had a single spool where the high-energy exhaust or jet was utilized directly to provide propulsive thrust. The single-spool jet engine consisted of a compressor, combustor, and turbine (generally termed the high-pressure spool). Because of the high-energy jet exhaust velocity, propulsive efficiency was low, particularly at lower aircraft speed. By introduction of a second spool called the low-pressure spool, a portion of the exhaust energy of the high-pressure spool can be used to drive a low-pressure turbine that in turn drives a low-pressure fan, or propeller in the case of turboprop engines, thereby reducing the engine jet velocity and achieving significantly greater propulsive efficiency, particularly at subsonic speeds. However, the technology programs that led to the development of the low-pressure spool were not well coordinated, and progress was slow and costly.

In 1988, the IHPTET program, a joint Air Force, Navy, Defense Advanced Research Projects Agency (DARPA), NASA, and industry effort, was initiated to better coordinate development of more affordable and robust higher-performance turbine engines. Phase I of the program was successfully completed in 1991; Phases II and III are scheduled for completion in 1997 and 2003, respectively. Phase III goals are very aggressive and include improvements of 100 percent in the ratio of thrust to weight for turbofan and 120 percent in the ratio of power to weight for turboshaft engines. Phase III embraces many technologies and is a

very comprehensive program for the entire government-industry propulsion team involving all six major U.S. turbine companies. The IHPTET program is an excellent example of the kind of progress that can be made through a coordinated goal-oriented team approach to R&D and is a good model to be used in other technology pursuits besides engines.

Core Engine Performance

In the more than 50 years since the jet engine was first developed, materials technology has contributed more to the steady and dramatic progress in performance, durability, maintainability, and cost than any other technology. During various periods, as much as 50 percent of the improvements made in performance resulted from advances in materials technology, particularly improvements in high-temperature nickel-based superalloys for the hot section and high strength-to-weight titanium alloys for the cold section (less than 1,000°F). The original Whittle and Von Ohein engines were limited to turbine inlet temperatures of about 1,400°F. Today's commercial engines operate at more than 2,800°F. Although turbine airfoil cooling techniques have certainly contributed to this truly noteworthy improvement, most of the increased capability continues to come from materials technology. An increase in turbine rotor inlet temperature is the single most powerful factor in maintaining the steady increase in specific core horsepower generated. Depending on the cycle and configuration, the improvement in specific core horsepower (horsepower per pound-second of airflow) has been utilized for a higher thrust-to-weight ratio in turbojet engines, better fuel consumption in high-bypass turbofan engines, and/or higher turboshaft horsepower per engine weight in turboprop engines.

Before discussing specific recommendations for propulsion technology investments beyond Phase III of the current IHPTET program, consideration should be given to utilizing a more fundamental metric by which to chart progress, as well as to judge whether further technology investments would be fruitful. The metrics of thrust-to-weight ratio and specific fuel consumption have been entirely appropriate for more than 50 years, as long as the configurations have been fairly stable and the only change has been from the original pure turbojet to the turbofan. However, as aircraft configurations evolve to incorporate augmented lift features (e.g., STOL, STOVL, or VTOL and directed energy), the ratio of thrust to weight may no longer be a fundamental measure of platform performance for tactical air platforms and is certainly not a good measure of engine performance. Specific core power and specific weight (weight per pound-second airflow) would be more fundamental measures of engine performance whether the core exhaust gas energy is used to drive a high-bypass fan propulsor, a shaft such as in a helicopter or turboprop, a lift augmentation fan, or a directed-energy weapon.

Improving specific core power is dependent primarily on operating at higher turbine inlet temperatures up to the theoretical limits of stoichiometric combustion. Based on current engines in production—if hydrocarbon fuels are assumed—the theoretical limit is up to four times higher than current specific core power figures. Successful achievement of the aggressive IHPTET Phase III goals would result in a specific core power improvement factor of about two, or roughly half of the theoretical limit. Achieving this goal would result in a dramatic improvement in air platform capabilities.

Ideal core performance is based on the ideal Brayton cycle, which assumes 100 percent component efficiencies and no parasitic air consumption (e.g., for cooling and leakage). The foregoing discussion has focused on core engine performance because it is the key enabling technology with the broadest applicability. The technical challenges associated with its achievement are presented below. Several other key enabling technologies and technical challenges are also presented.

Achieving IHPTET Phase II and Phase III Goals

Current Situation and Constraints

The aggressive Phase II goals, and particularly the more aggressive Phase III goals, currently depend heavily on nonmetallics technology. This quest for high-temperature, lightweight nonmetallics has been going on for many years with very limited success—clearly not enough success to permit incorporation into an engine for a manned tactical aircraft. The complete lack of ductility characteristics in nonmetallics has thwarted their utilization in most engine applications to date except for low-strain applications such as cold static parts.

Key Technology Enabler: High-temperature Metals

Conventional wisdom in the industry has been that metals have reached their peak. Consequently, substantial research and development for high-temperature metals basically has been abandoned. However, there are some credible activists in the industry who hold strongly to the view that metals could still be enablers in providing further increases in turbine temperature if R&D levels were increased to stimulate the necessary breakthroughs.

Other Contributing Technologies

Other technology thrusts that could contribute significantly to improved core engine performance include the following:

1. *Improvements in aerodynamic component efficiencies.* Aerodynamic

modeling within an engine is far more complex than the already difficult problem of modeling the external flow around an aircraft. Results of these efforts to date have produced dramatic improvements not only in reducing the design or development cycle but also in improving aerodynamic efficiency. It is believed that far more improvements in this technology are possible and could lead to additional improvements in core engine efficiency, not only for steady state but for off-design and transient conditions as well.

2. *Active closed loop flow path control.* Unequal heating and cooling of the rotor and stator drive the need for larger tip clearance to prevent case rubs and possible blade failure. By controlling the tip clearance throughout the operating engine, significant improvements in component efficiencies and thus in core engine performance could be achieved. Additionally, surge margin currently must be built into compressors to accommodate transients, inlet distortion, and deterioration. Improvements in closed-loop flow path control could provide overall improvements in efficiency and operability, as well as smaller, lighter components.

3. *Improved cooling.* Advanced high-temperature metals technology plus advanced turbine cooling are both critical to increasing turbine temperatures until uncooled metallics or nonmetallics become feasible and practical. The melting point of refractory metal alloys is more than 7,000°F. Currently 20 to 30 percent of core flow is used to cool the turbine metal parts. This represents a substantial penalty when the air that is compressed using turbine energy cannot be used in the cycle to produce core power and, in turn, thrust or shaft horsepower. Improved turbine cooling must therefore be pursued until such time as metallic or nonmetallic materials can be developed that do not require cooling.

4. *Variable cycle engines.* Requirements for takeoff, cruise, high-altitude operation, and supersonic operation are different, and ideally, engine cycles should be adjusted for each of these operating conditions. Since this has not been possible in the past, engine cycle selection for any given propulsion system has necessarily been a compromise. A variable cycle engine, in theory, would allow the propulsion system to be optimized for each specific flight condition. This of course is very simplistic and may not be entirely possible. Variable cycle engines, however, have been studied for many years in an effort to achieve some degree of cycle flexibility. To date, the complexity required to achieve a variable cycle engine appears to outweigh the benefits. However, most of the work to date has been proprietary to each propulsion company, and it has been difficult to obtain a fully objective assessment of the practicality of a variable cycle engine. An appropriate forum should be established involving the industry and other experts to examine variable cycle concepts realistically and fully for the purpose of making such an assessment. Figure 3.6 shows a schematic diagram of a variable cycle engine.

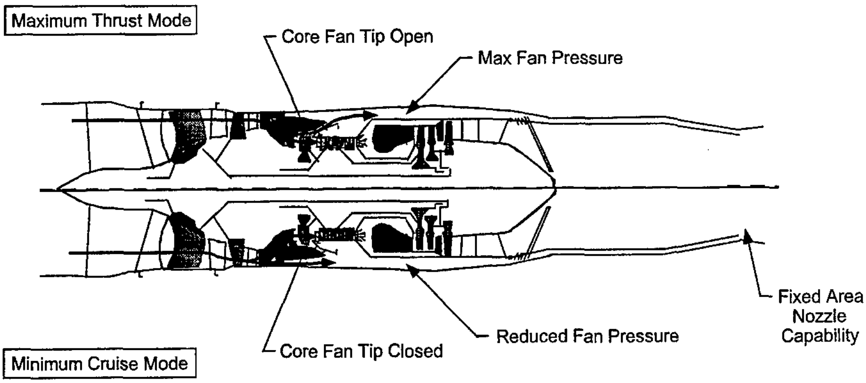


FIGURE 3.6 Schematic of a variable cycle engine. SOURCE: Courtesy of General Electric Aircraft Engines.

Potential Payoffs for Air Platforms

The payoff in improved core engine performance from aggressive pursuit of these technologies would have a dramatic effect on increasing the range and payload capabilities and reducing the size and therefore life-cycle cost of carrier-based CTOL and STOL or STOVL tactical aircraft, as well as removing other surface constraints to effective VTOL tactical aircraft operations.

Recommendations

The panel recommends that a comprehensive program be established modeled after the highly successful IHPTET program, to organize and fund coordinated research into each of these technology areas for improving core engine performance with goals for specific core power and specific weight that are 50 percent better than the IHPTET goals for 2003. Specifically, this program should address the following:

- *High-temperature metals and nonmetals.* It is strongly recommended that basic R&D in metals technology be significantly increased without restricting funding for what may be the very long term solution, namely, nonmetallics. The difficulties associated with practical designs utilizing nonmetallic materials that have almost no ductility are monumental, and these materials have yet to demonstrate sufficient progress for the majority of aircraft engine requirements. It is therefore recommended that R&D on nonmetals be targeted initially for use in expendable engines. Since the parts are smaller and development turnaround time is faster, the technology could be advanced more rapidly and at a more reasonable cost in expendable engines. In the meantime, research on high-tem-

perature metals has to be accelerated if progress is to continue in improving core engine performance.

- *Component efficiencies, flow path control and cooling improvements.* Continued R&D in these areas is essential to achieving the potential payoffs that lead to realizing the panel's vision of a lower-cost, more vertical and dispersed naval air capability at sea.
- *Variable cycle engines.* Although the chances of achieving a cost-effective variable cycle engine in the near term are probably remote, the payoff could be extremely significant to the air platforms of 2035, and it is therefore recommended that R&D be continued in variable cycle engines through a multicompany demonstrator engine program to fully explore and validate promising design concepts.
- *Environmental implications.* The panel was charged to consider environmental implications for new platforms and technology thrusts. From a propulsion perspective, the panel recommends that specific goals be established, as part of further IHPTET phases, for reduction in turbine engine emissions: NO_x reductions for aircraft engines and CO reductions for surface engine applications.

Adapting Large-engine Technology to Small Engines

Current Situation and Constraints

Scale effects make it difficult to apply large-engine technology to small engines. Clearance tolerances, which account for leakage losses, tend to remain constant regardless of engine size, and their impact relative to the small size of each airfoil or similar element is proportionally greater. Therefore, reductions in manufacturing tolerances and improved closed-loop flow path control can provide even greater improvements in transient aerodynamic modeling. For similar reasons, full-range aerodynamic modeling is even more important in small engines than in larger ones.

Technology Enablers

Additional R&D in full-range transient modeling and in reducing manufacturing tolerances is needed to enable small engines to benefit fully from technology improvements in large engines.

Potential Payoffs for Air Platforms

The Navy has unique requirements for small, heavy-fuel engines compared to land-based engines that run on light fuels. Engines for ship-based UAVs are but one example of this need. The inherent advantages in performance, weight, and reliability of turbine-powered engines, compared to reciprocating engines, coupled

with the adaptation of large-engine technologies would provide a very attractive and effective engine option for ship-based UAVs for reconnaissance and tactical strike, as well as for powering marine ordnance. For example, modest technology advances could yield significant improvements over today's small engines, including greater than 2:1 power-to-weight ratio, fuel economy competitive with diesels, and high reliability (time between overhaul >3,000 hours).

Recommendation

Apply large-engine technology to small engines by funding a heavy-fuel (JP5), small-engine demonstrator program with the following goals:

- Installed horsepower per weight ≥ 2.0,
- Specific fuel consumption ≤ 0.5, and
- Time between overhaul >3,000 hours.

Integrated Flight and Mission Control

Integrated Flight and Propulsion Control

Air vehicle designers have traditionally sought to provide inherent static and dynamic stability as well as controllability through fixed and movable airfoils. A good balance between inherent stability and controllability, based on consideration of size, operating speeds, and mission maneuvering requirements, was the measure of a designer's success. The objective in design integration of the propulsion system was to minimize the impact of propulsion on these other important design objectives, that is, to decouple propulsion from the stability and control equation and let the pilot be the flight integrator of control and propulsion through manipulation of stick and throttle. This traditional approach to the design of air vehicles has limited the space available to tactical aircraft designers.

Current Situation and Constraints

Current technology in aerodynamics; high-strength, lightweight materials; computers; and high thrust-to-weight ratio engines has greatly expanded the potential design space for combat aircraft. Evolutionary improvements in flight and propulsion control—from manual and boosted controls to digital, fly-by-wire systems—have allowed static and dynamic stability margins to be relaxed, which has opened up some of this new design space to designers. It has, for example, allowed the size, weight, and resultant structural strength requirements of aerodynamic stability and control devices to be reduced, making possible lower-cost, lighter-weight, high-performance fighters such as the F-16 Falcon. It has also allowed the use of destabilizing leading-edge extensions (e.g., on the F/A-18

Hornet) and canards (e.g., on some European fighters), to be used effectively to enhance maneuverability.

Although digital fly-by-wire control may have opened up additional design space for low-cost, high-performance aircraft in the heart of the flight envelope and at higher speeds, traditional aerodynamic stability and control devices lose effectiveness at extremely low speeds. VSTOL or VTOL aircraft such as the U.S. Marine Corps AV-8 Harrier and Russian YAK-38 Forger have overcome this problem by integrating, to some degree, the use of thrust vectoring both for propulsion or lift and for stability and control of takeoff and landing, and they have operated very successfully aboard ship. However, they still depend on conventional aerodynamic surfaces for stability and control at higher speeds and thus incur a penalty in range, weight, complexity, and cost for their VTOL capability over conventional tactical aircraft. The F-22 has taken integrated flight control a step further through the introduction of flight and vehicle management system concepts and mechanical pitch thrust vectoring, which is a by-product of its low signature afterburner nozzle design.

Key Technology Enabler: Multiaxis Thrust Vectoring

The X-31 program demonstrated the potential for multiaxis thrust vectoring to increase the maneuvering capability of conventional jet aircraft designs dramatically. The stability and control power of multiaxis thrust vectoring not only eliminate the drag, structural, signature, and weight and balance impacts of traditional tail section design but also greatly expand the usable flight envelope, particularly on the low-speed end. Designs having vectoring nozzles, particularly when combined with canards, enable thrust to augment lift for STOL and tighter low-speed tactical maneuvering. Vectoring nozzle designs open the door to thrust reversing for landing, which may also be employed beneficially in tactical maneuvering. The key is to approach flight control and propulsion from an integrated design perspective. This requires not only additional R&D but also further relaxing of existing stability and control requirements if designers are to take full advantage of these and other technology advances in future Navy tactical aircraft.

Other Contributing Technologies

The challenge in any design effort is to use available technologies creatively to achieve a high degree of synergism between the technical approaches employed to satisfy competing requirements. Nowhere is this more true than in aircraft design, where the cost, weight, and performance penalties of design compromises are so high. As in the F-22, there is potentially a high degree of synergism between vectoring nozzles and signature suppression. Likewise, there is potentially a high degree of synergism between signature reduction and the use

of thrust vectoring for stability and control of tailless aircraft, as well as enhancing cruise performance. Strong synergistic effects between thrust vectoring both for lift augmentation and stability and for control and improved low-speed aerodynamic performance, including STOL and VTOL performance, are also possible. In thrust vectoring itself, there is the potential to reduce synergistically the weight, complexity, and cost of mechanical vectoring, as well as the signature, through the use of fluidics. However, achieving this level of design integration and optimization in a timely manner and at an affordable cost is going to depend on the development of advanced design tools such as dynamic electronic prototyping.

Potential Payoffs for Air Platforms

The potential payoff of integrated flight control for ship-based tactical aviation includes not only the air platform itself but also the carrier. Reducing the vehicle weight, complexity, cost, and performance penalties for STOL could significantly reduce ship catapult and arresting gear performance requirements and, in turn, carrier aircraft structural weight and cost penalties, making common Navy, Marine Corps, and Air Force tactical aircraft designs a truly achievable objective. Stealthy, tailless STOL airplanes having good low-speed, level 1 handing qualities and improved cruise performance in reasonably sized, affordable, and survivable manned tactical aircraft would go a long way toward restoring the Navy's deep-strike capability. Even greater increases in range and reductions in size and cost could be achieved by manning such aircraft remotely. The key to achieving these payoffs, however, is well-coordinated, objective-oriented, long-term R&D in integrated flight control and design tool technologies.

Conclusions

The principal technology shortfall in flight control today is in low-speed stability and control. Achievement of a more affordable, vertical STOL or STOVL capability in the future will require substantial improvement in the technical approaches to attaining low-speed level 1 handling qualities, particularly for takeoff and landing under adverse conditions, that do not compromise stealth. A follow-on to the X-31 technology demonstration program has to be pursued to develop and exploit the applications of thrust vectoring to integrated flight stability and control for both signature reduction and STOL or STOVL capabilities beyond that currently planned for JSF.

High-capacity, Long-range Data Links

Current Situation and Constraints

Increasingly, the Navy is shifting to an operational concept wherein surveillance and targeting sensors are separated physically from the command node location, which in turn may be remote from the weapons launch platform. In the case of air platforms, no longer will the sensors, commander (pilot), and weapons necessarily be co-located in a single aircraft. Further, third-party targeting data sources and weapons magazines are proliferating. Examples of this evolving trend appear in such concepts as forward pass, cooperative engagement capability (CEC), the arsenal ship, and the piping of tactical situation data derived from a variety of off-board sources directly into cockpits.

This evolution offers promise for major improvement in the tactical flexibility and combat effectiveness of air platforms. Realization of this promise is not without challenges, however, because the operational concept is inhibited by the gross inadequacy of traditional communications equipment. To realize the potential benefit of this new concept, communications systems must be capable of reliable transmission of large amounts of data. They are now constrained by a lack of (1) bandwidth necessary to accommodate high-resolution imagery transfer; (2) processor capacity needed for target recognition and interpretation; (3) memory sufficient to handle massive amounts of archival data; (4) software to search the network quickly in order to provide commanders with tailored tactical information in a timely manner; and (5) for stealth reasons, the means to minimize signal emissions and the adverse impact of aperture size.

Key Technology Enablers

The Navy requires high-capacity, long-range data links that are reliable, secure, and supported by intelligent control, processing, and information search software. Fortunately, commercial technology in this area is experiencing explosive growth and the Navy can therefore leverage this development. Such data links can be leased directly or derived technically from the evolving worldwide, wideband commercial satellite and fiber networks, and from their supporting commercial terminals, switches, and stewardship software. Bandwidths have already grown from tens of kilobits to tens of megabits per second in five years; network routing is increasingly flexible and transparent to the user; addressing and formats are routine and network independent; and software agents routinely aid in search and analysis of data and in executing orders.

Payoff Potential for Air Platforms

High-capacity, long-range data links will permit physical separation of com-

mand, targeting, weapons control, and weapons delivery functions from the platforms performing these functions. Operational commanders will therefore be accorded vastly increased flexibility in employing air platforms. Introduction of this technology will accelerate the acceptance and employment of UAVs by the Navy and Marine Corps and will make available real-time tactical information to air crews and commanders. In summary, high-capacity, long-range data links that are reliable, secure, survivable, and countermeasure resistant are essential to opening up new air platform options for naval forces in the year 2035.

Recommendations

The Navy's task is to exploit commercial wide-band space and surface networks as well as special-purpose systems being developed by other Department of Defense (DOD) agencies. It must do this while maintaining the demanding link survivability and countermeasure-resistant performance required by mobile naval forces. This will involve the following:

- Monitoring industry and DOD organizations closely to keep abreast of fast-paced developments there;
- Encouraging industry to install features funded by the Navy that will facilitate Navy-unique exploitation of the technology; and
- Investing directly in focused projects that adapt these commercial technologies to the needs of naval aviation platforms, including developing antennas to prevent compromising stealth features of air and ship system nodes.

Signature Reduction

RF Signature Reduction

Reduced radar signature has been recognized for a number of years as a tactical advantage when operating against a radar-equipped enemy. A reduced signature enables combat leverage by collapsing an enemy decision and reaction time line. The leverage is beneficial for both improved lethality and improved survivability.

Current Situation and Constraints

A number of reduced radar signature aircraft are operated today—some reduced to a greater extent than others. Many would suggest that we are in the third generation of the applying this technology. First-order effects are attained through shaping, then by application of radar-absorbing materials and/or use of specially designed radar-absorbing structure. A corollary benefit may be to enhance the effectiveness of electronic warfare systems as an integrated package. The open

literature suggests that countertechniques may employ bistatic (receiver in a different location than transmitter) and electro-optical or infrared systems. These add to the challenge of providing a robust solution but are not without their own physical and operational difficulties. Analytical and design codes have been useful in determining proper moldline shapes and material applications and in characterizing new material and structural systems. These codes are challenged by the breadth of the problem to be addressed when considering bandwidth and the number of potential design solutions or material applications. Massive processing capability is imperative, and next-generation code development must be addressed. Of course, a companion issue is validation, which brings into focus the necessary test, modeling, scaling, and diagnostic capabilities necessary for effective and affordable design solutions. Finally, field experience suggests the need for improved fleet diagnostic, maintenance, and repair capability, as well as improved damage tolerance for some of the materials.

Key Technology Enabler: New Design and Analysis Codes

Advanced code development is progressing, enabled by substantial improvements in computational technology. Such systems employ massive core capability and provide for relatively rapid processing. This technology may be the fundamental enabler for continued progress in signature reduction as well as for product definition. Application of codes and processing techniques facilitates definition of new material properties, manufacturing processes, system applications, and test measurement techniques.

Remaining challenges, from both a design and a technology perspective, include reducing the number of apertures; elimination or mitigation of gaps and protuberances; providing lightweight, robust materials and attachment systems; and analytical or empirical correlation of test results to full-scale applications. Additional issues include maintaining a balance between shape and aerodynamic, structural, and vehicle handling performance.

Other Contributing Technologies

Signature reduction interacts with several other technology areas discussed in this report. An integrated vehicle design demands attention to aerodynamic cruise performance, high-lift aerodynamics, and IR signature reduction. Aerodynamic codes have an analogue in electromagnetic codes. Some particular vehicle applications may be facilitated by incorporation of integrated flight and propulsion control. Certainly, the technological progress in lightweight, high-strength composites; dynamic electronic prototyping; and reduced-cost, low-rate production facilitates development and incorporation of this technology.

Potential Payoff for Air Platforms

Continued progress and successful incorporation into new vehicle design will provide improved lethality and survivability of tactical combat and airborne reconnaissance systems, with attendant reduced acquisition and support costs. Application of the technology to other naval systems should provide a greater combat detection edge across the board.

Recommendations

- RF signature reduction efforts should be focused on providing advanced, wide-band, material systems as an integrated design solution. This implies continued advance code development and validation, including improved experimental modeling, scaling, and diagnostic techniques.
- Additional efforts are required to provide quick turnaround and user-friendly fleet diagnostic, damage repair, and maintenance techniques.
- Integrated R&D and design efforts should be focused on reducing the number of apertures and generally providing greater moldline fidelity and continuity. The design and application effort should include integration of vehicle shaping and material systems for future air vehicles such as the JSF and advanced combat and surveillance UAVs.

IR Signature Reduction

Infrared signature reduction has lagged RF signature reduction in the past, largely because of the weight, complexity, and cost of the technical approaches pursued, such as direct shielding and active cooling. The relatively higher IR signature levels have tended to compromise achievements in RF stealth by enabling IR detection and tracking for missiles and cueing for RF sensors to counter RF stealth. Reducing IR detectability, especially in the medium- and long-wave spectra (3 to 5 and 8 to 12 μm, respectively), to levels comparable to RF detectability would eliminate the use of IR as a countermeasure to RF stealth and greatly increase the overall effectiveness of current RF stealth technology as well as reopen low-altitude airspace to strike operations. However, achieving these levels of IR stealth will require a complete rethinking of the problem and a coordinated R&D program to bring together all of the technologies that can contribute in a synergistic way to a more cost-effective IR stealth approach.

Current Situation and Constraints

To some extent, special paints or coatings can reduce airframe emissions at their design wavelengths, but not to levels of detectability comparable to RF stealth. Special passive surface treatment of exposed metal engine parts poten-

tially can do the job in the rear quadrant, but the physics employed in this surface treatment is not a practical solution for the rest of the airplane. There are also manufacturing challenges and questions about long-term degradation in a sooty, hot gas environment that still have to be resolved, and further R&D is needed before such surface treatments can be put to practical use on engines.

Key Technology Enabler: Thin-film Coatings

The Department of Commerce is currently pursuing an advanced technology program (ATP) in thin-film technologies to replace paint on aircraft. Preliminary results indicate that thin-film coatings will be more durable than paint, will offer savings of up to 25 percent in unit cost and 50 percent in life-cycle cost over conventional aircraft painting, and will virtually eliminate the toxic vapor and waste problems associated with painting and stripping operations. In addition, additives can be put in the film adhesive to inhibit corrosion, which when coupled with a more protective coating could provide very significant reduction of aircraft skin corrosion problems. However, the most significant aspect of film coatings for military aircraft is that the same passive surface treatments used for engine parts could easily be applied to film surfaces in the manufacturing process and potentially produce the same results that have been achieved on engine parts. Used together, surface treatment of exposed engine parts and airframe film coatings could have the potential to reduce the level of IR detectability to that of RF.

Other Contributing Technologies

Although the physics of the passive surface treatments involved is understood, substantial R&D work remains to be accomplished to get them into production. The techniques used to fabricate treated metal surfaces for testing are not necessarily suitable for manufacturing actual engine parts. The effects of exhaust gas contamination need to be investigated and ways found to mitigate this if it proves to be a problem. Likewise, film top coatings have to be optimized for the long-term durability of the film and the effectiveness of surface treatments in an operating environment, which includes intense sun and rain exposure, as well as exposure to dust, salt, solvents, and other contaminants. Techniques for application, repair, and removal likewise have to be optimized. Although some of this is being addressed in the Commerce Department's ATP, signature aspects are not. These aspects include not only the environmental effects on surface treatments but also the development and refinement of analytical tools to model and optimize such treatments in both the IR and the visual spectra.

Potential Payoff for Air Platforms

There is potentially a very strong synergistic payoff for naval aviation in thin-film technology as a replacement for paint, in terms of both life-cycle costs and corrosion protection and of significant reductions in IR and visual signatures for no more weight and half the life-cycle cost of paint, excluding the hazardous materials cost aspects of paint. The potential payoff is even more dramatic when the cost, weight, and impracticality of active cooling required to achieve the required levels of IR signature reduction are considered; these are well beyond the capabilities of today's special paints. Bringing IR detectability back into balance with RF would leverage the investments already made in stealth and could nullify the shoulder-mounted IR missile threat in the types of Third World challenges where the risk to U.S. aircrew is an important political consideration in deciding whether or not to engage. This technology would also be applicable to ships and other craft or vehicles needing protection against IR detection and IR missiles.

Recommendation

The Department of the Navy should initiate a comprehensive IR signature reduction program to coordinate research in film coatings, as well as other surface treatment techniques, with the objective of reducing aircraft detectability by IR sensors to levels commensurate with current and projected detectability by RF sensors. The opportunity exists for the Navy to leverage ongoing research into thin-film coatings as a paint replacement by investigating how such coatings can be used for signature control as well as corrosion protection.

Design and Manufacturing Processes

Dynamic Electronic Prototyping

Tremendous strides have been made in advancing the state of the art in computer-aided design and manufacturing. Designers can now work in a three-dimensional design environment that automatically highlights component fit and interference problems, which greatly accelerates the design process. Completed CADAM designs can now be transmitted directly to automated production equipment on the factory floor to fabricate parts and speed up the manufacturing process. However, aircraft design is still dependent on building developmental flying prototypes to validate performance and weed out functional integration problems. This process adds years and billions of dollars to development time and cost, and to life-cycle costs, and mission performance can be affected when basic design problems are discovered too late in the development process to be fixed properly. The current, iterative design, build, test, analyze, and fix ap-

proach to aircraft development is expensive and time consuming and accounts for a significant percentage of the 15 years typically required to field new aircraft.

Current Situation and Constraints

Commercial advances in modeling and simulation software over the past few years, particularly in support of the entertainment industry, have far outstripped those made in the previous 20 years in support of defense aerospace. Although much of this commercial progress has been in visual effects, the underlying software is equally applicable to defense modeling and simulation needs and has, in fact, contributed to our current national war gaming simulation capabilities. Virtual reality, a laboratory novelty five years ago, has already been employed effectively in evaluating human factors aspects of NASA space station designs and commercial ship designs. Campaign models, such as those used to plan Desert Storm operations, and, to a lesser extent, system effectiveness evaluation tools have also benefited. Despite the advances in modeling and simulation capabilities and in CADAM capabilities, the two have not been integrated, and aircraft designers and engineers still rely on separate specialized software tools for just about every aspect of design development.

Key Technology Enabler

The three principal software tools used in aircraft development are three-dimensional CADAM for design, finite element analysis for structural engineering, and computational fluid dynamics for aerodynamic optimization. A number of additional software tools are used in the process, however. For example, there are separate codes for modeling RF stealth effects and computational means of modeling just about every other conceivable aspect of aircraft design from airframe aeroelasticity and avionics to hydromechanical subsystems and basic material properties. There has been no strong commercial incentive, however, to commit the talent, time, and money to pull all of these tools together into a common, integrated, user-friendly program for designers and engineers, and this is unlikely to happen anytime soon without strong government sponsorship and funding support.

The computational power and modeling codes required for electronic prototyping already exist and, if properly integrated, would allow the Navy to build high-fidelity fully functional prototypes in cyberspace and test them for proper operation under simulated dynamic environmental conditions. This would allow the design and engineering to be refined and matured on the computer an order of magnitude faster than the design, build, test, analyze, and fix process used today in the development of new aircraft. Subcontractors could submit functional software models of their proposed components in a standardized format that

would permit rapid installation and functional checkout in the electronic prototype. Weight and balance and cost data could be updated, and subsystem and component failure modes could be exercised in a total system context. Fault isolation system checkouts could be performed, and component installation, removal, and replacement could be evaluated to optimize maintainability. In fact, the entire manufacturing process could be planned, evaluated, and optimized on the computer well in advance of committing to tooling.

Other Contributing Technologies

Although many of the engineering software tools already exist, their integration will likely require development of a prototyping software architecture and a user-friendly system of templates for inputting design, material, functional characteristics, and other data. The underlying models need to be compatible with the new modeling architecture, and new models may have to be created to fill in any missing elements such as gust loading, carrier wake turbulence, and field runway effects. The objective would be to model both the aircraft and its operating environment as closely as possible yet still allow lower-fidelity preliminary designs to be exercised to facilitate the design and engineering optimization process. The concept is to provide engineers with a means of quickly quantifying performance, weight, producibility, and cost tradeoffs as the detailed design evolves.

Potential Payoffs for Air Platforms

Historically, new aircraft development programs get into trouble because the performance, weight, and cost implications of the selected design and technical approach are not known in sufficient detail early enough in the development process to achieve the stated operational requirements within the program's schedule and remaining funds. Dynamic electronic prototyping would close this information gap. The performance, weight, and cost of the selected design and technical approach could be quantified early, allowing program time and budget to be spent productively on achieving stated requirements and making a smooth transition to production. High-fidelity dynamic electronic prototypes would also facilitate the development of variants and, if maintained for each operating configuration, could be used to engineer and test engineering change proposals, update support, and investigate in-service problems. Thus, electronic prototyping not only would reduce development time costs and risks but also would reduce life-cycle costs and facilitate in-service improvements in combat capability and readiness to extend the airplane's useful service life. These benefits would apply to the use of electronic prototypes in the design, development, and life-cycle support of ships and submarines as well.

Recommendation

The development and integration of the software necessary to perform dynamic electronic prototyping must be recognized as a major software engineering undertaking and handled in much the same way as other major new acquisition programs. To be successful, it must be pursued as a team effort, combining the talents of the aerospace industry and the ultimate user, as well as expertise from the commercial software industry, universities, and government. The panel recommends that such a program be organized and funded as a multiyear effort, with high-level Navy Department or DOD sponsorship. The program will require a well-staffed Navy program management office, capable of organizing, integrating, and contracting for the scope of effort required from the exceptionally wide range of technical expertise that must be brought to bear to define the requirements, do the research, design the architecture, set the standards, and write the core software and application programs necessary to achieve a true high-fidelity dynamic electronic prototyping capability.

Reduced-cost, Low-rate Production

A dramatic change has occurred in the defense industry: namely, rates of production have reached record lows, and affordability, or cost, is a dominant parameter. Conventional wisdom suggests that costs increase naturally as the quantity and rate of production decrease. Significant advances in design, fabrication, assembly, and tooling process technology are needed to enable affordable modernization of our combat forces.

Current Situation and Constraints

Most air vehicle production practices are the outgrowth of those employed while the United States was increasing force structure significantly in response to a Cold War threat and to serious regional conflicts (e.g., Korea and Southeast Asia). Significant defense buildups resulted in significant quantities of weapons systems and weapons. For example, in the late 1960s, the F-4 Phantom production rate reached 72 per month. Today's production rate peaks at 24 per year for the F/A-18 and less for other systems. In addition, the aerospace industry has experienced massive contraction (40 percent reduction in jobs) and consolidation, raising significant issues of maintaining job skills on the shop floor and retraining the current production work force. Legacy systems, processes, and production operations are labor intensive by tradition. Reworking and cost of quality have been the norm. Traditional approaches led to a high number of parts, tools, fasteners, and station moves (of subassemblies) and to the introduction of errors. Having more operations required in the system is a fundamental contributor to more mistakes.

Quality-enabling techniques, first introduced into the commercial world, are

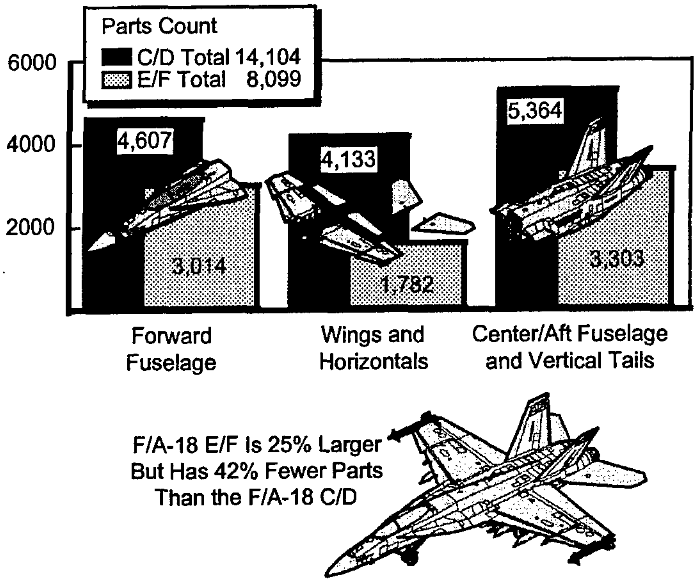


FIGURE 3.7 Design for manufacturing and assembly: the F/A-18 E/F, a true success story. SOURCE: F/A-18 E/F Program Office, Naval Air Systems Command, Arlington, Va.

now finding their way into the defense business. The use of computer-aided design is a basic enabler for development of a single, three-dimensional, solid model database used for design, analysis, tooling design, and manufacturing (both fabrication and assembly). A fundamental requirement for achieving high-quality, low-cost, low-rate production is to exploit the digital database and its resultant electronic mockup. Techniques include feature-based design and design for fabrication and assembly using the most modern fabrication and tooling processes to facilitate cost savings, as well as a step function reduction in the number of parts, tools, and fasteners in an assembly or subassembly. An example is the F/A-18E/F, where concentration on design for manufacturing and assembly and new fabrication techniques have led to increased quality and a significant reduction in parts count; see Figure 3.7.

Key Technology Enabler: Large Unitized Structures

The panel has chosen to label large unitized structures as a key technology. More appropriately it may be labeled a key technology result or a technology process driver. This means that large unitized structures represent an approach to significant quality improvement and cost reduction, enabled primarily by

computer aided design technology and, as an adjunct, dynamic electronic modeling.

These elements lead to a definition of the required process technology for integrated design, machines (fabrication), tooling, and assembly processes. These draw on such technological progress as high-speed machining and superplastic forming for metals, fiber placement and stitched resin infusion for composites, development of composite tools with a metallic vapor barrier for the autoclave, use of laser theodolites for assembly with a closed loop to the design database, computer-aided work instructions and superimposed virtual image registration for assembly, and use of stereolithographic processes to develop investment castings. These examples, some of which are depicted in Figure 3.8, are merely starting points. Significant challenges remain for joining technology (welding, bonding, electromagnetic drives for rivets); high-speed machining and cutter development for hardened metals (titanium and steel); tooling (expendable tooling, tool costs, and tool life); and supportability and maintainability of large unitized structures. All of these elements should be the focus of an enduring Navy ManTech program.

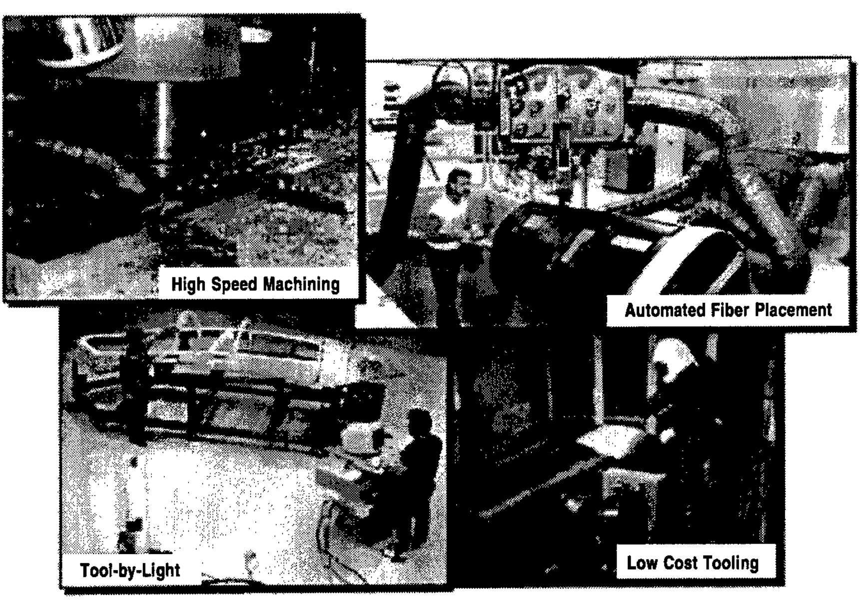
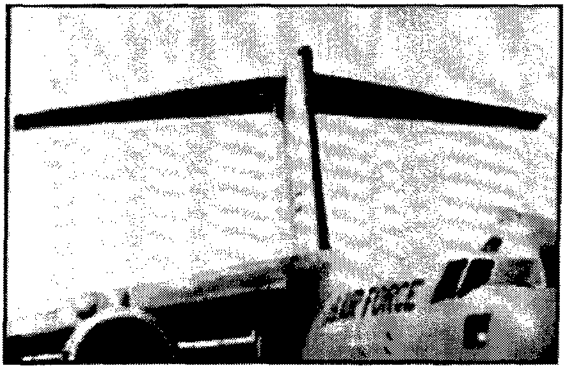


FIGURE 3.8 Examples of manufacturing process initiatives. SOURCE: Courtesy of McDonnell Douglas Corporation.



Horizontal Tail Redesign Using Best Practices Has Yielded:
- 88% Parts Reduction
- 82% Fastener Reduction
- 56% Tool Reduction
- 20% Weight Reduction
- $33.5M C-17 Acquisition Cost Reduction (53%)

FIGURE 3.9 Bottom line results: benefits of design in manufacturing and assembly realized in the C-17 transport program. SOURCE: Courtesy of Wright Laboratory Manufacturing Technology Directorate, Wright Patterson AFB, Ohio.

Other Contributing Technologies

The above technology set interacts with several others in this report. Principal enablers exist via dynamic electronic modeling. Results of progress here affect virtually every element previously noted and have a direct interplay with the area of lightweight, high-strength composites.

Potential Payoffs for Air Platforms

Success in this area can have a first-order effect on force structure modernization through reduced cost of acquisition and ownership. Product quality and performance (weight) should also improve markedly. This may, indeed, be the single most important leverage for future defense systems, not only for air platforms but also across the board as the principles are applied. One prominent example is a newly redesigned C-17 horizontal tail, which has realized significant cost and weight reductions; see Figure 3.9.

Recommendations

- Navy ManTech efforts should emphasize the principle of reduced parts, tools, and fasteners in the development and manufacturing processes for both metallic and composite structures. Manufacturing process development should be conducted to extend high-speed machining from aluminum to hard metals

such as steel and titanium. Joining techniques, such as diffusion bonding and friction-stir welding, should be exploited to provide quality subassemblies and assemblies and to provide leverage for the use of near net shape casting and HIP forgings. Advanced casting and forming techniques should be exploited for repeatable large-part production, and should focus on producing near-net-shape parts to eliminate both material waste and machine time.

- Advanced tooling concepts should be explored in conjunction with the fabrication and assembly techniques noted here and in the discussion of composite structures. The guiding principles should be expandable-rate tooling (i.e., suitable for low rate, modified at some later point for increased rate) and reduced number of unique tools (via design for assembly and integrated manufacturing processes to obviate assembly steps, e.g., high-speed machine subassembly to eliminate sheet metal buildup).
- Integrated design and production efforts should be modeled, along with process cost, to allow cost-based decisions up to and including factory layout to reduce production cost and cycle time.

SUMMARY OF ENABLING TECHNOLOGIES

Table 3.2 lists the 12 key enabling technologies identified by the panel and indicates their impact on important air platform characteristics and costs. Aggressive development of these technologies will affect acquisition and life-cycle costs positively and in a major and fundamental way. Developing these technologies is essential to improving key aircraft design attributes such as cruise, takeoff, and landing performance and to enhancing combat survivability, particularly in subsonic speed regimes.

Applications of Enabling Technologies

These enabling technologies are applicable to manned and unmanned designs, and to conventional as well as various short or vertical takeoff and landing concepts. Further, they permit physical separation of command, targeting, sensor, weapons carriage, and weapons control functions from the platforms, air or surface, that perform the functions. Table 3.3 shows how these technologies affect the development of new concepts.

Although these technologies also apply to the kinds of aircraft operating or being developed today, they were selected because they open up future aircraft and carrier platform options that are not otherwise attainable with current programs and R&D plans. Developing the proposed enabling technologies and exploiting the platform options thus opened up could move naval aviation, in the years ahead, in the following directions:

TABLE 3.2 Air Platform Characteristics and Costs: Impact of Enabling Technologies

Enabling Technology	Greater Endurance and Range	Higher Thrust-to-Weight Ratio	Lower Landing Speed	Enhanced Survivability	Less Development Time	Reduced Acquisition Cost	Lower Life-cycle Cost
Laminar flow control	X					X	X
High-lift aerodynamics			X				
Lightweight, high-strength composites	X	X		X		X	X
Core engine performance	X	X				X	X
Variable cycle engine		X	X	X		X	X
Adapting large-engine technology to small engines	X	X					X
Integrated flight and propulsion control			X	X		X	X
High-capacity, long-range data links				X			X
RF signature reduction				X		X	X
IR signature reduction				X		X	X
Dynamic electronic prototyping				X	X	X	X
Reduced-cost, low-rate production						X	X

TABLE 3.3 Aircraft and Air-Capable Ship Concepts: Application of Enabling Technologies

Enabling Technolgy	Subsonic Aerial "Truck"	STOL	Enhanced VTOL	Enhanced STOVL	UAV Long Endurance	UAV Sea-based Support	UAV/Sea-based Strike Fighter	Reduced Dependence on catapults and Arresting Gear	Broadened range of Viable CV Sizes	Increased CV Config-uration Options	CV/LHD Hybrid
Laminar flow control	X				X						
High-lift aerodynamics		X	X	X			X	X	X	X	X
Lightweight, high-strength composites	X	X	X	X	X	X	X	X	X	X	X
Core engine performance	X	X	X	X	X	X	X	X			
Variable cycle engine		X	X	X				X	X	X	X
Adapting large-engine technology to small engines	X				X	X					
Integrated flight and propulsion control		X	X	X		X	X	X	X	X	X
High-capacity, long-range data links	X				X	X	X				
RF signature reduction	X				X	X	X				
IR signature reduction	X				X	X	X				
Dynamic electronic prototyping	X	X	X	X	X	X	X				
Reduced-cost, low-rate production	X	X	X	X	X	X	X				

- Systems that embody performance enhancements principally in air weapons and sensors instead of the platforms themselves.
- Subsonic aerial trucks as weapons carriers, target designators, and sensor platforms. Here, speed and maneuverability would no longer be principal design drivers. Also, the truck concept will facilitate improved cruise and endurance characteristics and make signature reduction more easily achievable and less costly.
- A more vertical force—VTOL, STOVL, and STOL. The mix of such platforms and CTOLs will be determined by the success of vertical designs in fleet operations and the size and configuration of future aviation ships.
- Widespread use of land- and sea-based UAVs for surveillance, reconnaissance, targeting, and a variety of support missions. UAVs for lethal purposes may follow.
- Reduced dependence on high-capacity catapults and arresting gear.
- A mix of aircraft carrier sizes.

Fighter and Attack Missions

Exploiting the enabling technologies will facilitate a shift in emphasis from an overfocus on platform performance to a focus on weapons, sensors, and communications. Thus, a fighter or attack aircraft in the future need not be a wholly self-contained system that can do everything on its own. Instead, it can serve as a de facto reusable intermediate stage of a broader weapons system in, for example, the role of weapons carrier, or solely as a sensor platform controlling missiles launched from ships, land sites, or arsenal airplanes. Such platforms also can be manned or unmanned.

Subsonic Aerial Trucks

The need for high-speed, very maneuverable, and, consequently, expensive air platforms would be minimized by substituting utilitarian subsonic trucks that incorporate modular mission change packages where sensible. These trucks may or may not have on-board sensors, depending on the mission. They could draw on tailored off-board information derived from long-endurance UAVs, satellites, Air Force platforms, national technical means, and other battle group assets. The aerial truck concept is also an attractive candidate for the several nonlethal support missions now flown by sea-based aircraft.

The subsonic truck has the cost advantage of being less expensive to develop, manufacture, and operate than vehicles in today's high-speed fleet. Given improved laminar flow techniques and advances in engine efficiency, improved cruise and endurance performance is ensured. Placement of propulsion components is simplified, which in turn will facilitate the development of STOL vehicles and improvements in VTOL and STOVL designs.

A shift to predominately subsonic air platforms also facilitates the achieve-

ment of reduced RF and IR signatures in future designs. This is attributable to greater flexibility in airframe shaping, application of signature-reducing coatings, placement of engine inlet and exhaust ducts, placement and shaping of sensor and communications apertures, and in the instance of a weapons-only arsenal truck, elimination of radiation by sensors and communications.

More Cost-efficient Systems

The acquisition cost for future aircraft needed to carry out today's fighter and attack missions can be reduced by eliminating the high-speed flight requirement, no longer essential tactically or for survivability and employing advanced design and manufacturing processes. Operating costs will be lower because of the better aerodynamic cruise performance of new subsonic designs, as well as improvements in engine-specific fuel consumption. Combining these attributes with reliable and secure, high-capacity, long-range data links will yield a force that is less costly overall to procure and operate, on a dollars per target killed basis, than today's technology allows.

Unmanned Aerial Vehicles

UAVs offer obvious great potential benefits in surveillance, reconnaissance, and targeting, although these are only beginning to be demonstrated in the field. Additionally, UAVs promise reductions in aircrew manning and attendant training costs, as well as elimination of political risk associated with current manned aircraft reconnaissance missions and one-time punitive strikes in which downed aircrews are in danger of becoming hostages. Exploiting the enabling technologies will assist the Navy and Marine Corps to benefit from the kinds of concepts that spring from the high level of interest in UAVs by Congress and other DOD components.

Long-endurance Systems

Very long endurance or long-range UAVs that often can operate only from distant airfields, offer great promise to naval forces at sea despite their inability to fly from ships. Technical advances such as improved subsonic laminar flow; high-strength, low-weight composite airframes; improved propulsion efficiency; and reliable, secure, high-capacity data links over long distances give these systems their unusual performance and make operations in support of air and surface naval forces feasible.

As an example, the Tier II+ High Altitude Endurance system, now being developed by DARPA, can fly 2,500 nautical miles to an operating area and remain on station for two days before returning to base, all the while providing area and spot data from synthetic aperture radars, moving target indicators, and

electro-optical and infrared sensors via satellite or direct line-of-sight downlink to naval commanders at sea and Marine Corps air-ground task forces ashore. Matters of ownership, tasking authority, flight control, payload control, and imagery access must be worked out, but integration into the Navy and Marine Corps of commercial data link and satellite technology will make possible full exploitation of the potential of very long-range or long-endurance UAV systems.

Sea-based Systems

The panel sees VTOL, STOVL, and STOL designs as the sea-based UAVs of choice, with VTOL solutions going beyond current rotary wing technologies such as the tilt rotor and conventional helicopter. Air vehicles with ability to take off and land vertically or in short distances make sense for naval applications because they can operate from flattop aviation ships and other surface vessels with smaller, partial helicopter-like flight decks.

UAVs Permitting Offloading Functions

By employing land- and sea-based UAVs for a variety of support missions—reconnaissance, surveillance, targeting, weapons control, EW, tanking, and long-range ASW and AEW—the flexibility of a naval task force at sea can be enhanced considerably. Commanders could offload certain support functions from carriers and amphibious aviation ships, thereby freeing flight and hangar deck space and turning these air-capable ships into all-strike or all-assault lift platforms. When naval forces operate at great distances from friendly airfields, the long-endurance UAV assures the commander of needed support while still permitting him to engage in high-intensity strike operations and ship-shore assault.

Lethal UAVs

Unmanned vehicles designed for lethal purposes are concepts to be explored as the enabling technologies mature, experience is gained in nonlethal applications, and trade studies help identify the most cost-efficient approaches. Such concepts range all the way from stealthy, loitering, long-endurance UAVs that dive into targets of opportunity to a highly capable air vehicle much like today's F/A-18 that is flown remotely by a pilot located in a command module on board a ship. In between these extremes might be a Tomahawk-like missile equipped with dynamic retasking capabilities and a large, possibly stealthy, subsonic aerial arsenal truck, described above, carrying weapons that can be launched on remote command.

Networked Warfare

The Navy is currently leading development efforts in CEC as part of its air defense approach. The recent introduction of an airborne mode in the network will now enable ships best positioned to engage a threat to do so on the basis of tracking and fire control data contributed by other ships in the task group.

At the present time the development effort in CEC is focused on integrating the air node into the network strictly as an airborne relay. The next step is to enable the air node to contribute fire control quality data to the net from its own on-board sensors, with a vision of eventually adding airborne shooters to the netted air defense capability. The panel believes that the current focus of netted warfare should be expanded to include offensive operations against surface targets by aircraft, submarines, and surface ships, with airborne sensor platforms—very likely UAVs—performing terminal guidance where necessary in a forward pass mode of operation.

The netting of all warfare platforms by a common cooperative engagement architecture for both defensive and offensive combat operations would greatly expand the inherent warfighting capabilities of all platforms for littoral warfare, including support of Marine Corps forces ashore. Air platforms in particular would benefit greatly from the ability to employ off-board weapons. Aircraft size, weight, and cost could be greatly reduced since ordnance payload and carrier bring-back weights are design drivers in size and strength requirements and, consequently, in cost—including the cost of stealth.

Support and Special-mission Aircraft Functions

Challenge and Opportunity

Perhaps the greatest potential for effecting beneficial change exists in providing the functions now resident in support and special mission aircraft. Mission categories include patrol, antisubmarine warfare, tanking, airborne early warning, surveillance, reconnaissance, electronic warfare, and logistics support. Some of these planes are not carrier capable and operate solely from shore bases; others, such as fixed-wing logistics aircraft, cycle to and from the fleet. However, significant numbers of support and special-mission planes are regular elements of the carrier air wing, constituting about 25 percent of the wing's complement. The functions they perform give the carrier battle group flexibility, including its ability to operate independently of other forces if required, an attribute much valued by senior commanders.

However, this flexibility comes at a price. The support elements occupy 35 percent of available deck space aboard carriers, space that might be used to embark additional strike fighters. If the support functions can be offloaded but still remain available to the commander, the CV could be turned into a pure strike

ship. Here, it would serve as a refueling site and munitions magazine proximate to the target area, reloading and rapidly cycling fighter and attack aircraft. Battle group combat effectiveness would be enhanced, and the cost per target killed should be reduced.

Commanders now have the option to change the mix of aircraft in an air wing and offload support aircraft. However, provisions must be made for the kinds of support these planes provide, support that is not available if the battle group is operating at a distance from friendly airfields. Hence, as a practical matter, creation of an all-attack carrier is not feasible today in many tactical situations.

New Option—Off-board Support

The enabling technologies that facilitate development of long-endurance or long-range UAVs, sea-based UAVs, and the aerial truck make possible offloading these functions to the degree desired. Support mission functions are naturals for unmanning, with very long-endurance or long-range UAVs that remain on station two days or more, constituting the backbone capability. The generally nonlethal nature of support functions also should facilitate early introduction of unmanned aircraft as current programs demonstrate reliability and UAVs therefore gain broader acceptance.

Long-dwell surveillance or reconnaissance aircraft, with large-aperture antennas, would provide continuous tactical intelligence to both battle group and expeditionary force commanders without any necessity for sea-based flight operations. Also, naval expeditionary task forces without CV battle group support would benefit from improved situational awareness of their own and enemy forces without the interference to ship-shore lift operations that carrying organic reconnaissance platforms would induce. Patrol squadron (VP) could easily evolve into such a support force, becoming a shore-based element of the carrier's air wing.

Sea-based manned and unmanned support aircraft could be positioned on ships other than CVs and LHDs. In concert with long-range systems operating from shore, this would reduce or eliminate flight deck congestion on both aviation ship types and would speed up turnaround of strike aircraft and troop lift rotorcraft.

Implications for Aircraft Carriers

Introduction of new air platform concepts made feasible by development of the 12 key enabling technologies described above will have a profound effect on the design of future aircraft carriers and amphibious aviation ships. A more vertical aircraft complement broadens considerably the range of viable CV and LHD size options in the following ways:

- *Nimitz size.* New air platform concepts would enable a large CV to

generate significantly more sorties than can an air wing patterned after today's CTOL wing configuration. Sortie totals also can be increased dramatically by offloading support functions as noted above. The operational flexibility and economies of scale inherent in a large carrier likewise remain factors to be considered.

- *Medium-tonnage CV.* With a vertical air wing, a medium-tonnage carrier could generate sorties equivalent to today's Nimitz air wing.
- *Small CV.* Operating a vertical air wing reduces the tonnage threshold below which a carrier is considered nonviable.
- *CV-LHD (amphibious assault ship) hybrid.* A mission-flexible carrier suitable for littoral warfare might be possible. Depending on the task force mission, such a ship could embark strike fighter aircraft, Marine Corps lift and attack rotorcraft, or a mix of types. Since the next-generation aircraft envisioned by the panel can operate from aviation ships across a wide spectrum of sizes, this opens up the possibility of the Navy buying a high and low mix of aviation ships. These ships could include Nimitz-like CVs suitable for large-scale operations and smaller flattop aviation ships for less demanding situations.

Payoff: A Potential Sea Change in Naval Aviation

The benefits resulting from aggressively developing the key enabling technologies outlined in Table 3.3 will have a significant impact on both air platforms and their base ships, as summarized in Box 3.1. The Navy and Marine Corps have an opportunity to effect a sea change in the naval aviation of 2035 if the requisite technologies are developed and the platform options that spring from them are exploited. This force would differ materially from one that would result from the normal requirements and acquisition process; it would be different in character, composition, capability, flexibility, and cost. In turn, it would have a dramatic and positive overall impact on future naval forces.

RECOMMENDATION

The R&D path now being pursued by the Department of the Navy may limit its choices for air platforms that will follow on current development programs such as the Joint Strike Fighter program and a possible common support aircraft.

Accordingly, the panel recommends that an air platform technology development plan be undertaken that comprises R&D funded by non-Navy entities, traditional Navy-funded programs centered on needs unique to the Sea Services, and most importantly, the 12 enabling technologies identified in this chapter, whose development should be vigorously pursued in IHPTET-like fashion. By doing so, Navy and Marine Corps leadership will have in hand a range of options on its technology buffet line when the time comes to develop platforms to enter operational status in the year 2035 and beyond.

BOX 3.1
Naval Aviation of the Future

- Moving toward a more vertical force—STOVL, VTOL, and STOL
- Subsonic aerial trucks as new, utilitarian naval air platforms
- Very long-endurance, long-range UAVs a principal naval forces asset
  - — High-quality surveillance, reconnaissance, and targeting information in real time
  - — Capability for offload of support aircraft from carriers
- More flexible carrier deck loading
  - — CVs as all-fighter or attack warfighters, or as
  - — Littoral warfare support ships with few or no VF or VA
- Broad range of viable aircraft carrier sizes and configurations
  - — Large CV to small CV with same aircraft types embarked
  - — Hybrid, multimission aviation ship (CV-LHD) as littoral warfare platform
- More cost-efficient force as a result of the following:
  - — Lower aircraft acquisition and life-cycle costs
  - — Greater aircraft deck loads per ship ton than today
  - — Increased CV sortie generation rates
  - — Efficiency of all-strike "arsenal" aircraft carrier
  - — Reduced manning due to more reliable systems, introduction of UAVs
  - — Lower training costs because of unmanning, less CV landing training for "vertical" air wing
- New air platform decisions necessary only as enabling technologies are proven

4

Submarine Platform Technology

OVERVIEW OF FUTURE SUBMARINE PLATFORM TECHNOLOGY

Vision of Submarine Platforms for 2035

Over the next 40 years rapid proliferation of high-technology systems will render nonstealthy platforms and weapons systems increasingly vulnerable. The inexorable global spread of modern technology will allow hostile nations to increase their sea-denial capabilities through improved surveillance, enhanced reconnaissance, rapidly expanding information technology and precision weapons. This growing ability to inflict significant casualties on forces that can be detected and tracked easily places a premium on the value of stealth. U.S. forces, required to establish and maintain sea control when and wherever the national interest requires, will need maximum stealth capabilities. The increased value of, and emphasis on, stealth will likely result in increased reliance on submarines in future naval operations.

Submarine systems clearly fit into the definition of "sunrise systems," recently espoused by the Chief of Staff, U.S. Air Force: ". . . systems which incorporate stealth, high mobility, precise targeting, minimum logistical requirements, and operational autonomy."

Submarines can position early and covertly to strike key threat command-and-control nodes with precision missiles or to deploy ground forces and provide support. Submarines provide a stealthy platform with great range, mobility, endurance, payload potential, and survivability. In many hostile environments, the submarine may be the only survivable platform. Future submarines will offer

a significant degree of flexibility and reconfigurability, both internally and through the use of off-board vehicles, sensors, and weapons; they also will accommodate rapidly emerging technology to improve current capabilities and to enable new roles and missions. Advanced battle management systems that enable cooperative engagement with other naval forces will enhance the effectiveness of submarine participation in complex missions including antisubmarine warfare, strike operations, theater and national missile defense, and the deployment of ground forces for specialized warfare. The greater relative survivability (based on stealth, mobility, and endurance) of the submarine and the potential for expanding the range and depth of mission effectiveness suggest a greater role for submarines in the Navy of 2035.

In striving to attain this vision of future submarine platforms, a major objective must be to develop submarines and systems that can be acquired, operated, and maintained in the most cost-efficient manner possible. This drive for greater affordability must address the submarine's entire life cycle from design to disposal. Cost savings can be pursued aggressively through virtual design and prototyping, design for modular construction and technology insertion, system elimination and simplification, maintenance avoidance, and finally, ship disposal. Taken together, innovation in submarine design and the application of automation can result in a significant reduction in the manpower required to operate and maintain future submarines.

Warfighting Objectives Driving Technology

As naval warfare has evolved and matured, submarine mission areas have steadily broadened. Continued mission expansion will be driven by the ever-increasing value of stealth, endurance, and mobility. The following warfighting objectives serve to define important military capabilities desired by the year 2035; thus, they identify technologies to be pursued:

1. *Sea control.* The exercise of sea control and the certain denial of that control to adversaries are fundamental missions of the submarine. If a submarine is in an operating area, other platforms operate at its sufferance.
2. *Precision strike.* Covert on-station presence, early and for lengthy periods, is necessary in order to identify, observe over time, and destroy when directed potential threat command-and-control nodes and other vital targets with precision submarine-launched missiles.
3. *Covert insertion.* Deployment of ground forces of various numbers, configurations, and capabilities offers the advantage of determining optimum timing by covert and, if necessary, extended on-site observation of the tactical situation.
4. *Coordinated fire support.* Submarines must be able to launch strikes in support of forces both ashore and afloat, utilizing various weapons. In the near

future, the OHIO class Trident submarine could be configured to carry and launch between 100 and 200 tactical missiles.

5. *Intelligence collection.* The capability for tactical and national intelligence collection over an extended period is needed to provide forward covert surveillance both prior to and after onset of hostilities.

6. *Theater antisubmarine warfare.* This capability includes protection of sealift, both through constricted littoral areas and in the open ocean, as well as strategic ASW—antisubmarine warfare operations conducted against adversarial nuclear-powered ballistic missile submarines (SSBNs). Strategic ASW encompasses the ability to monitor the activities of potentially unfriendly SSBNs during peacetime, as well as to destroy them when so ordered.

7. *Antisurface warfare.* Attacks against traditional merchant and military targets must include the capability to destroy small, shallow-draft vessels. This capability also supports the submarine's effectiveness in conducting a blockade, either overt or covert, and in detecting, tracking and intercepting narcotics or arms control violators.

8. *Strategic deterrence.* The most broadly acknowledged submarine mission area provides the final line of direct defense for the U.S. homeland. As the nation's most survivable strategic deterrent force, carrying more than half of its strategic nuclear warheads, the Navy's force of SSBNs requires the continuous infusion of new technology to guarantee its strategic operational security and effectiveness over the decades ahead.

9. *Missile defense.* The future ability of submarine forces to participate as an integral element of the national missile defense (NMD) and theater missile defense (TMD) systems, especially as a missile platform forward-positioned off a hostile coast, will require further technology development. The potential for boost-phase intercept of enemy missiles and the potential for limited antiair capability for self-defense and forward-area air-denial operations are both areas of opportunity for further development.

10. *Mine operations.* Covert mine location, as well as possible disablement by submarines operating in hostile waters, is a prime element in thwarting an enemy's sea control-denial capability. In addition, the covert and remote placement of mines by submarines can deny an enemy the use of its own littoral waters and severely limit its naval surge potential.

Primary Technology Focus Areas

Six primary technology areas have been identified by the panel that couple to the military warfighting objectives noted above. The impact of emerging technology can be strengthened if developed and applied in the context of a systems engineering approach whereby the synergies afforded by technology develop-

ment on a broad front are applied in an integrated manner to the technology focus areas listed below.

1. Stealth is the fundamental enabler of submarine naval warfare, enhancing the ability to operate anywhere, at any time, covertly as the strategic and tactical deterrent. The technical challenges associated with enhancing the stealth of underwater vehicles, including both active and passive measures, are difficult and complex and necessitate an integrated development approach both to capture the synergies available and to ensure that the appropriate tradeoffs are made between different submarine signatures and other performance parameters.

2. Architecture, including hull structure, shaping, and materials, encompasses the use of innovative design, materials selection, and total systems integration to significantly improve submarine performance, payload capacity, and stealth while improving manufacturability and reducing costs. The goals of advances in architecture include greater speed for the same power input by reducing drag, greater stealth through the reduction of acoustic and nonacoustic signatures, and simplified fabrication using creative structural design and advanced materials.

3. Sensor and connectivity improvements include hull designs that incorporate embedded sensors, which may allow for the elimination of the bow-mounted spherical array sonar systems, and enable advanced connectivity capabilities such as laser communications. For acoustic sensors, emerging technologies will expand the options for location of outboard sensors, as well as improve the performance of these sensors, including enhanced performance at higher submarine speeds, while reducing their cost and complexity. Enhanced connectivity in all aspects of command, control, communications, computers, and intelligence (C^4I) should enhance the submarine's interoperability with all elements of naval, joint, and combined task forces. In the electromagnetic regime, the future submarine will require improved systems for intelligence collection, early warning, and robust connectivity without compromise of covertness.

4. Payload technologies include a wide-ranging menu of weapons and devices that the submarine can carry for offensive and defensive purposes when operating independently or as a component of a joint or combined force. Released from the constraints of conventional designs, the payload of a submarine can include a range of capabilities from torpedoes and missiles to unmanned offboard underwater or airborne vehicles, antisatellite weapons or satellites themselves, and various ground forces with their equipment.

5. Power-density improvements include the compression of the entire power plant in length, diameter, and weight to permit the design of more effective submarines with equal or greater payload and lower self-noise at high speed. The design flexibility gained from reducing power plant weight and size can be translated into reduced noise signature, optimal hydrodynamic shaping, and improved overall

performance. Improved power density coupled with an integrated electric power and propulsion system will yield an on-board energy source for advanced military applications such as directed energy beam weapons and hydraulic munitions (directed jets and high-energy vortices).

6. Off-board vehicles deployed by submarines will significantly extend the battle space and enhance sensing capability while reducing risk to the submarine and its crew. UUVs and UAVs will improve the effectiveness of forward-deployed submarine forces. Advanced technology and design are required for packaging energy, sensor, and handling requirements. Submarine wide-band high-data-rate (HDR) communication with off-board vehicles will be required to enable integrated force employment.

Summary

One conclusion of the 1988 Navy-21 study stated: ". . . Submarines with increased capabilities could become major, multimission capital ships of the fleet . . . driven by the need to reduce vulnerability of forces . . . and by the opportunities offered by advanced missilery and quiet submarine technology . . ."[1] This conclusion is as valid today as it was a decade ago.

The submarine is an indispensable platform in the U.S. Navy's tactical and strategic deterrence forces. The credible exercise of sea control and the certain denial of that control to adversaries hinge on a complete and up-to-date submarine naval warfare capability. The characteristics that endow the submarine with its unique warfighting capabilities are stealth, mobility, and endurance, coupled with flexible payload capacity and advanced information systems. Technology development for future submarine forces should be focused on building on and enhancing these characteristics.

The enabling technologies that support submarine naval warfighting objectives should be pursued in the context of total platform integration together with innovative cost management techniques, a process rapidly maturing in modern submarine design. The benefits of automation and other technological changes can lead to increased capability with reduced manning and maintenance while controlling affordability in both the short and long term.

The U.S. Navy should continue to design and build the best, most capable submarines possible, given the technology available and the long-term defense requirements of our maritime nation. This design should provide for the continuing introduction of rapidly evolving technology through either advances in soft-

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[1] Naval Studies Board. 1988. *Navy-21: Implications of Advancing Technology for Naval Operations in the Twenty-First Century, Volume 1: Overview,* National Academy Press, Washington, D.C., p. 41.

ware or modular hardware replacement throughout the life of the platform. At the same time, the Navy can stimulate the development of submarine technology by espousing a broad and imaginative vision of future submarine naval warfare capabilities.

TECHNOLOGY FOCUS AREAS

Stealth

Stealth is the fundamental attribute that enables a submarine to operate undetected for extended periods in forward areas and to execute multiple missions with great effectiveness and limited risk. Submarine stealth is neither absolute nor static, however, and it must be reevaluated and improved continually as the scope and effectiveness of opposing detection systems increase.

It is understood that stealth is a complex attribute not amenable to a single or point solution. An integrated systems approach to stealth enhancement is imperative; correcting only four of five stealth deficiencies is futile because the deficiency that remains can be sufficient to betray the submarine's presence. Thus, a number of technologies should be considered and applied in concert—and integrated closely with the submarine's overall architecture—to minimize all components of the submarine's signature. Stealth technologies can be divided into two broad categories: acoustic stealth and nonacoustic stealth.

Acoustic Stealth

Improving acoustic stealth requires both attacking the acoustic energy created by the submarine's machinery and its passage through the ocean and reducing the acoustic energy that the platform reflects from an opponent's active sonar transmissions. In addition to reducing the submarine's detectability, acoustic signature reduction also serves to improve the submarine's own passive sonar performance. Opportunities to enhance submarine acoustic stealth are available in the areas of radiated noise reduction and external flow control, including machinery noise suppression and advanced propulsor design; active sonar target strength reduction; acoustic transmission security; and own-ship signature monitoring.

Radiated Noise Reduction

The objective of radiated noise reduction is to realize a step reduction in ship-generated noise, including noise produced by the propulsion and internal machinery. Future efforts should emphasize low frequencies and the effect of higher speeds. Significant reductions may result from the use of active mounts, isolated structures, advanced hull treatments, and double-hull construction, as well as hull

and appendage shaping, vortex control, adaptive coatings, and the selective use of additives such as polymers and microbubbles. In addition, silencing weapons-launch transient noises can greatly reduce ship detectability in combat.

Active Mounts. Active mounts, which employ piezoelectric materials or other types of actuators to actively cancel mechanical vibration, can greatly attenuate major noise paths from the machinery to the hull. Such mounts can be incorporated into a system of shipwide active noise control techniques that will work together to maximize the effect of this technology at minimal cost. Successful implementation of this technology would reduce the need for specialized quiet machinery and individual mounting of machinery. Active mounts will be a component of specially designed isolated structures, such as the Modular Isolated Deck Structure (MIDS) designed for the New Attack Submarine, and another project involving active control of machinery platforms being developed under the auspices of the Office of Naval Research.

Isolated Structures. Isolated structures are being developed to work with and enhance the overall performance of active mounts. Novel structural concepts that channel noise transmission to the hull so as to result in optimized mount performance and minimized hull radiation hold considerable promise. New developments should focus on improved low-frequency performance.

Advanced Hull Coatings. Advanced hull coatings offer several benefits: first, they serve as a barrier that attenuates radiated noise emanating from within the hull; second, they can reduce reflected acoustic energy, that is, acoustic target strength; finally, hull coatings can reduce flow-induced noise and drag. Again, new development should be focused on reducing low-frequency radiated noise. These treatments will require novel approaches to attack both specific low-frequency tones and wide-band low-frequency noise. A combination of special hull treatments covering various frequency regions, isolated structures, and active mounts is well suited but not limited to double-hull ship concepts.

Double-hull Construction. Double-hull construction, over all or part of the submarine's hull structure, can serve to streamline the shape of the hull hydrodynamically, and possibly enable an entirely new approach to submarine acoustic stealth. Rather than isolating equipment that radiates acoustic energy individually, on rafts, or both, the double-hull approach would attack acoustic quieting by working from the outside of the submarine in. The technological challenge here lies in developing hull coatings that could provide the required acoustic attenuation at a reasonable cost and would impose no significant maintenance penalty.

Weapons Launch Transient Noise Silencing. Weapons launch transient noise

silencing is a key to improving ship survivability. Advances in both weapons and launch systems are needed to achieve the necessary reduction of transient noises associated with current torpedo handling and launching systems. These new external systems should be developed with transient noise minimization as a fundamental objective.

External Flow Control

The objective of external flow control is to influence the flow field around the submarine to reduce noise, increase propulsion efficiency, enhance maneuverability, and reduce the hydrodynamic signature, especially when operating near the surface. A more complete understanding of the flow field around full-scale submarines is needed to facilitate development of efficient and effective methods of flow control. Potential applications of this understanding might include the techniques discussed below.

Pressure Field Modification. The pressure field around the submarine can be modified faborably by changing the shape of the hull and its appendages, optimizing the location of the propulsor, redistributing the pressure field through suction and blowing, and other innovative techniques such as riblets, vortex generators and annihilators, and adaptive surfaces. The challenge here is to integrate the ship configuration wisely with all functions that affect the pressure and velocity fields around the hull and through the propulsor.

Integrated Propulsor. Integrating the propulsor with the hull and the flow field around the hull could reduce drag and propulsion noise. For a propulsor to achieve these goals, it must be integrated with the entire flow field around the hull as well as the hull itself. Effective integration will require addressing a number of fluid flow problems, including issues involving the basic physics of fluid phenomena, that currently are not well understood.

Separation Control. Separation of flow from the hull or appendages results in turbulence, which in turn increases drag and flow noise. Although some sources of separation can be controlled or eliminated with good design practices, the challenge will be to adapt the flow field during maneuver or other conditions that might otherwise induce separation. Changes to the shape or the pressure field that are controlled properly offer the opportunity to totally eliminate separation of the flow field. Such changes to shape and material properties appear to be within the capabilities of emerging smart materials and structures (SMS) technologies.

Polymer Ejection. Full-scale testing has shown that polymer ejection not only will reduce the self-noise of a submarine, but also will decrease the drag of the hull and the radiated noise generated by the propulsor. Speed increases of 10 to

15 percent and reductions in self-noise exceeding 10 dBs (decibels) at certain frequencies for a given speed are possible. A current stumbling block is an appreciation of the amount of polymer that must be carried for particular roles—e.g., burst speed, tactical speed, and routine patrol—and how and where on the submarine it should be distributed. Employment of improved polymers and delivery systems, abetted by other technologies such as microbubbles, can address these issues. Polymer ejection can be deployed locally to improve sensor performance and reduce signal processing requirements.

Electromagnetic Turbulence Control. Electromagnetic turbulence control (EMTC) involves the interaction of magnetic and electric fields in a conducting medium (such as seawater) to generate forces. If the forces act inward toward the hull, they will dampen turbulence in the boundary layer, which will reduce both radiated noise and drag. If they act on only one side of the hull, they will produce maneuvering forces. EMTC is still in its infancy and presents major technical challenges such as power requirements, electromagnetic signature, weight, environmental compatibility, and practicality. Additional research is required before the feasibility and benefits of this potentially promising technology can be evaluated properly.

Active Sonar Target Strength Reduction

The objective of active target strength reduction is to minimize the submarine's reflectivity with respect to active sonar. Target strength can be reduced by special hull treatments (active and passive) and by geometric design and shaping.

Special Hull Treatments. Hull treatments have the potential to decrease reflectivity across the frequency range of future sonars. Passive treatments will generally have to be thick to gain significant performance improvements. Those treatment concepts that will minimize material compressibility are expected to have the least impact on ship buoyancy effects. Development of active treatments may address the difficult low-frequency range and minimize the need for very thick passive treatments. Both active and passive treatments should be integrated with hull treatments designed to reduce radiated noise (discussed above) and with structural design concepts. Double-hull concepts may be attractive in this regard.

Hull and Appendage Shaping. Shaping, along with structural design concepts, can be developed to minimize both reflection back to an active sonar source and radiation caused by an active sonar. Shapes can be designed to minimize reflections but must be coordinated with hydrodynamic and hydroacoustic performance. Structural designs must be developed to minimize reradiation of active

sonar transmissions. There will be some synergy of these designs with radiated noise reductions.

Acoustic Transmission Security

Although a basic objective in radiated noise reduction is to eliminate the transmission of acoustic energy into the ocean, some operations require deliberate acoustic transmissions. Thus, there is a need to minimize the detectability, classification, and locatability of such deliberate transmissions.

Acoustic Communications Security. High-data-rate acoustic communications between submarines and unmanned undersea vehicles, surface ships, or other platforms will be increasingly important to support submarine missions such as coordinated ASW, launch and recovery of special operations forces, and mine countermeasures. Mission security can be compromised unless the enemy's ability to detect, classify, and locate these transmissions is minimized. Providing security and the necessary data rate over tactically useful ranges offers a considerable technological challenge; mimicking the acoustic background is one possible technique.

Active Sonar Security

Active sonar at various frequencies is an essential sensor in many tactical situations (e.g., diesel-electric submarine prosecution and mine detection). Low probability of intercept (LPI) sonars have been developed in the past but have not achieved the degree of security desired. Further technology development in this area is required.

Own-ship Noise Monitoring

Advances in the ability to predict and control own-ship radiated noise are necessary to continue to ensure stealth and mission effectiveness. The key to improvement is the development of both an instrumentation suite and the algorithms to provide real-time radiated noise assessments; these assessments should address radiated noise amplitude and directivity. Algorithm development is the most challenging aspect of this system, relying on sophisticated finite element and statistical energy analysis techniques.

Nonacoustic Stealth

A submarine's nonacoustic signature also must be managed in a coordinated and integrated fashion; each offending artifact should be addressed individually

and with regard for the ship's overall signature. This includes designing an inherently stealthy platform and then utilizing intelligent signature management techniques when conducting mission operations. Nonacoustic signature will become increasingly important as the role of the submarine is expanded in both littoral and open ocean areas. Some specific nonacoustic signatures that require the application of advanced technologies follow.

Radar

Radar can be used to detect hardbody (submarine or mast) and wake signatures. Recent investigations have shown that radar cross-section reduction technologies developed for aircraft can be applied affordably to the submarine platform. The integration of external flow control, discussed earlier, can lead to submarine and antenna configuration designs with reduced wake and other surface signatures.

Visual and Infrared Detection

Visual and infrared detection can be utilized to detect both the submarine itself and its wake. Camouflage technologies exist that can significantly reduce visual and IR detection ranges. These include passive paints and coatings and smart chameleon coatings that adapt to the background environment. These technologies have been proven for both air- and land-based applications. A major challenge in applying them to the submarine is addressing seawater-submarine environmental issues.

Electromagnetic Signatures

Low-frequency electric and magnetic field signatures are currently being reduced through the use of several control systems. At present, these systems run independently and with little active capability. In the future, they should be fully integrated with full, active closed-loop capabilities.

Conclusions

Stealth is the most salient feature of the submarine platform and one that must be maintained and enhanced if submarines are to continue to operate effectively in support of Navy and Marine Corps missions. The strategic and tactical value of submarine stealth is likely to grow in the future as surface ships become increasingly vulnerable to the combination of the widespread availability of visual satellite data and relatively low-cost GPS-based guidance systems. Improv-

ing underwater stealth is a complex and technically challenging endeavor and one that will require an integrated, systems engineering approach if it is to achieve significant advances across the entire range of the signature spectrum.

Accordingly, the successful attainment of significantly improved submarine stealth will require an integrated approach across a broad front of technology development, characterized by stable, long-term funding and a high degree of coordination among seemingly disparate technology programs.

During the course of its study, the panel identified two significant bottlenecks that might impede the advancement of stealth technologies. The first of these is the lack of development of computational fluid dynamics tools specifically tailored for problems associated with acoustic and nonacoustic underwater stealth. CFD is a rapidly advancing field that offers important tools for increased understanding of the physical processes that contribute to the generation and propagation of detectable submarine signatures, but these developments in computational capability have not yet been systematically applied to Navy-specific problems. For this reason, there is a need to continuously develop powerful computational research tools, including CFD and nonacoustic modeling, specifically tailored to underwater stealth applications.

The second bottleneck is the uncertain support for naval test ranges and facilities. The complex problems associated with improving underwater stealth are not amenable to analytic solutions and therefore must rely on modeling and computational simulation. Making progress in such an environment is highly dependent on the ability to test accurately the designs indicated by the results of simulations and feed those test results back into the models. Near-final and final designs will require extensive real-world testing. To that end, both sub- and full-scale acoustic and nonacoustic test ranges and facilities—such as those at Lake Pend Oreille and Behm Canal—will be vital components of any stealth development program.

Architecture

Submarine architecture encompasses the integrated analysis and design of hull structure, form, and materials. An integrated approach is required because changes to individual architectural components affect hydrodynamic and operational performance. The realization of electric drive, an integrated stern, and large lightweight conformal arrays is expected to confer significant performance benefits.

Hull Structure, Form, Materials

Active Signature Control

Advanced technology has seen a great reduction in component size as well as in the total displacement of the new nuclear-powered attack submarine (NSSN)

from the large space and weight requirements that underpinned the nuclear-powered attack submarine (SSN) 21 design. This technology will initially be incorporated into the new SSN and so will sustain *Seawolf*'s substantial gains in noise quieting but will realize those gains with a smaller-volume ship. Follow-on advancements in this application will completely reverse the trend to larger systems and equipment in order to achieve the most demanding quieting goals. With the attributed relationships of displacement to cost, this has the potential to reduce the production cost of U.S. submarines.

Boundary Layer Control

A number of active boundary layer control technologies are currently in the research phase, including some that draw on the application of emerging MEMS and nanosensor technology developments. These have a potential for relatively high payoff but are currently in the earliest stages of development and will require further nurturing before they can be brought to fruition. Nearer-term benefits may be realized from selective boundary layer suction and advanced control techniques. Antifouling techniques and coatings may also be relevant to boundary layer control. The payoff for longer-term technologies, such as electromagnetic flow control, is more uncertain.

In addition, there are combinations of more conventional flow control techniques that can be exploited synergistically. The integrated benefits resulting from the multifaceted programmatic approaches to the varied contributors to disrupted smooth flow around the hull will continue to improve submarine architecture significantly. This disrupted flow is known to affect ship speed, stealth, and maneuverability. Recent advances in computational fluid dynamics may provide further opportunities to understand and ameliorate this problem.

Improved Sail Shaping

Advanced geometries will be of benefit to future-generation submarines. Alternative sail designs have been conceptualized that provide additional volume for maintenance access, external stowage, and mission payload configurability. Various geometries and materials have been identified that could provide improvements in hydrodynamic performance and reduced target strength and, in the long term, provide space and surface area for embedded sensors. Improved sail shaping could reduce life-cycle cost by facilitating maintenance.

Biofoulants

Antifoulant surfaces are necessary to prevent the development of slimes (microfouling) and the attachment of natural marine organisms (macrofouling) on the hull, appendages, and propulsor. The challenge is to identify long-lasting

and environmentally acceptable biocides or bioresistant surfaces or other means to inhibit or remove micro- and macrofouling.

Hydraulically Smooth Surfaces

Surfaces with roughness elements on the order of 10 microns for full-scale submarines will reduce drag and associated flow noise by reducing energy losses. This is a first step toward flow control because, given smooth surfaces, other boundary-layer control techniques will become more efficient. Since the surface roughness of present submarines is about 200 microns, the challenge is to identify and develop materials with the desired smoothness that are inexpensive to produce, apply, and maintain. As part of the integrated approach to submarine stealth, research to develop this material should be coordinated with the development of advanced acoustic coatings.

Composite Materials

Advanced nonmetals, including glass-reinforced plastics and new silicones, can be used for lightweight structures or coatings to enhance the durability, functionality, and producibility of structures that will be exposed to hostile operating environments.

Smart Materials and Structures

The smart materials and structures (SMS) currently under development in a DARPA program may eventually be used to control the flow field and to manage the state of the boundary layer of the hull and the propulsion inflow. Besides providing control of shed vorticity, it is postulated that these can simultaneously reduce both drag and the acoustic signature of the platform, as well as enhance the submarine's maneuverability. This program could incorporate the application of multipurpose coatings, that is, surface treatments that are anechoic, decoupling, antifouling, and drag reducing.

High-strength, Low-alloy Steel

High-strength, low-alloy steel (HSLA) is currently used in submarine applications. Additionally, the use of undermatched welding for HY 100 pressure hull applications has been approved. Future testing is still necessary before HSLA 100 can be approved for such applications. If it were approved as a logical low-risk step, it has the potential to provide real fabrication and affordability benefits, eliminating preheating while the undermatched welding technology eliminates the need for the costly postweld heat treatments currently required.

Microelectromechanical Systems

Embedded sensing and actuation are possible in various applications throughout a ship for monitoring equipment and detecting unusual activity and potential problems in real time. Predicated on its ultimate uses and associated costs, MEMS technology could also be a primary contributor to manpower reduction on all Navy units.

Conclusions

As future submarine designs are conceived, evaluated, and implemented, the final product will be enhanced greatly by applying a broad and inclusive approach to submarine architecture, bringing together into a synergistic whole the myriad technologies (including those discussed above), innovative concepts, and processes that submarine design requires.

Sensor Performance and Connectivity

Significant improvements that will affect the design of future submarines can be expected in sensor performance and connectivity. Electronic technology will permit these advances and expanded submarine employment concepts will require them. The substantial relationship between sensor and connectivity improvements and the enhancement of submarine design requires an integrated approach to improvement. For instance, envisioned sonar sensor improvements will enable major changes in hull design, while new connectivity equipment may well have a notable effect on hydrodynamics due to potential requirements for topside devices, new antennas, and fairings.

Producibility and modernization also require integrated consideration. The wide disparity in the pace of technology development for electronic and information systems versus that for ship design means that technology insertion must be planned carefully.

Sensors

Projected technology improvements such as the introduction of fiber optics and conformal arrays and the exploitation of research into phenomenology will result in major upgrades in capability.

Conformal Acoustic Velocity Sensing

Conformal acoustic velocity sensing (CAVES) devices will include an array of velocity field sensors used in place of pressure field sensors. They will enable a

much better noise decoupling, at greatly reduced weight, over previous conformal arrays, and can be placed over large areas of the hull using fiber optics. Further significant benefit will come from elimination of the spherical sonar array, freeing up weight and volume and permitting greater flexibility in arrangement.

Flow Noise Suppression

Flow noise suppression techniques can be used to simplify signal processing at high tactical speeds. These techniques include many that should be incorporated into a full-scale hydrodynamic approach to submarine design. Some specifics include biofoulants to reduce slimes and marine growth on the hull and propulsor, hydraulically smooth surfaces that avoid the drag-induced effects of roughness elements, the use of flow control to reduce the complexity of signal processing, conditioning the inflow to the propulsor, and the ejection of polymers and microbubbles to reduce drag and minimize acoustic and nonacoustic signatures.

Active Acoustics

Exploitation of active acoustics has the potential to be a major factor in countering the continuing reduction in passive ranges. Operationally, the most attractive approach lies in the use of off-board sources to avoid own-ship detection. Provisions for handling the necessary vehicles have to be considered, but the largest technology implications are for the high-power active sources themselves and for bistatic or multistatic processing. Research and development to meet this most important military requirement has begun, but the technology has to be resolutely pursued.

Connectivity

The dramatic development of information warfare technologies and exploitation of the attendant possibilities for greatly improved connectivity have been identified as prime drivers of naval force structure for the foreseeable future. It will be necessary for submarines to be fully capable of networking with other naval forces, including shore installations, surface ships, aircraft, and other submarines. Because of their typical far-forward deployment and their requirement for stealth, providing this networking capability will present a serious technical challenge. Nonetheless, high-data-rate, wide-band, secure communications are a must in the atmospheric regime and have to be accommodated to the preservation of submarine nondetectability.

Essentially, the same requirements for information transfer exist for underwater linkage between submarines; provisions for LPI transmission and reception

have to be included in advanced submarine design. Acoustic mimicking of the marine background is also possible. Foreign navies have developed a series of underwater communications systems that provide moderate data rates for ranges out to 100 km and mimic local marine life. There are limitations, but the covert aspect is obvious.

As an example of advanced technology to be incorporated in submarines, lasers have an obvious potential for vertical connectivity to and from submarines, with realistic possibilities on the horizontal plane as well.

Cooperative Engagement Battle Management Systems

Battle management systems that can enable cooperative engagement with other Navy and Marine Corps forces, as well as with other joint and combined forces, will be a required element in the total suite of systems for future submarines. Receiving data from a wide range of communications links and fusing them with information derived from its own on-scene sensors, including those that are off-board such as unmanned underwater vehicles (UUVs), unmanned aerial vehicles (UAVs), and fixed active or passive array fields, to generate the tactical picture and fire its weapons, will greatly expand the submarine's battle space and its mission effectiveness. Certain weapons will also evolve, providing signal-level data feedback and intersensor coherent processing with the submarine and its sensors to achieve greater accuracy and enable more rapid prosecution of offensive combat operations.

Relay Devices

Other off-board systems for connectivity enhancement include both recoverable and expendable relay devices. These can permit covert communications to a safely remote transmitter that, in turn, could inhibit or completely deny the enemy an ability to track the transmitting unit even during necessary communications.

High-speed Processors and High-data-rate Antennas

High-speed processors and HDR antennas are improving rapidly today in industry as well as in military applications. The submarine force could benefit from the incorporation of these technologies and the application of commercial equipment and programs wherever possible.

Conclusions

Sensors are the eyes and ears of the submarine, and improved connectivity

will greatly enhance the submarine's combat effectiveness. The panel thus concluded the following:

- Improved sensor technology, especially the utilization of fiber optics and conformal arrays, will become an essential element of future submarine forces as potential targets become ever quieter and more difficult to detect.
- To the degree that, from a C^4I perspective, the submarine is indistinguishable from any other unit of the force, improved connectivity will be required for submarines to function as fully integrated units of joint task forces. Improved connectivity is the key to enabling a cooperative engagement capability.

Payload Technologies

Future submarine missions enabled by the submarine's stealth and relative invulnerability include national or theater missile defense; precision high-volume fire support of ground forces; launch, control, and possibly recovery of off-board air and undersea vehicles for remote sensing and weapons delivery; remote mine reconnaissance and offensive mining; delivery and control of multiple ground force elements; and deployment of off-board seabed sensors. Execution of these missions will require the submarine to carry and deliver new offensive and defensive weapons, including regenerative weapons, that are smaller and more lethal. Thus, the development of submarine payload technology must support development of the weapons, vehicles, and other payload deliverables, as well as the means to place weapons on target and, where appropriate, recover some of the devices. This development of payload systems must seek to achieve the greatest possible commonality, flexibility, and modularity so that the submarine's payload configuration or loadout can be modified readily as dictated by mission objectives.

Payload Technologies to Support Weapons Delivery

Smaller Missiles

Missile size reduction that incorporates the use of precision guidance, more energetic propellants, and more effective warheads offers great potential to increase the rate and volume of firepower that the submarine can deliver.

Half-size (Length) or Smaller-diameter Torpedoes

Half-size (length) or smaller-diameter torpedoes can increase the number of missiles carried by submarines, thereby extending combat endurance without increasing volume. Size reduction in mobile mines, possibly the ability to launch several swimout or mobile mines simultaneously, can provide similar improvements in firepower. In addition to size reduction, advancements are needed that

provide a quick-reacting, high-speed weapon for close-aboard ASW engagements and a long-range standoff ASW weapon cued by off-board sensor targeting. Both missile-delivered standoff ASW weapons and quiet, long-endurance ASW torpedoes should be considered.

Technologies critical to high-speed weapons are power density, reduced drag hydrodynamics (e.g., supercavitation), and guidance and control. Longer-endurance weapons require increased energy-density propulsion, stealthy operation using closed combustion systems, and intelligent guidance and control with a communications link (e.g., fiber optics) to the firing platform to provide updates on targets and to provide tactical assistance in a severe countermeasures environment.

External Weapons Launchers

External weapons launchers could replace part or all of the submarine torpedo tubes and the torpedo room, thus eliminating up to 500 tons of displacement as well as a complex structure that is expensive to build and represents a major lifetime maintenance cost. The incorporation of external weapons also reduces the 21-in. limitation on weapon diameter so that weapons launchers or canisters of different sizes and shapes can be accommodated without costly pressure hull work. Development is required in weapons ejection technology (e.g., advanced gas generators), acoustic launch transient quieting, launch hydrodynamics, commonality with surface ship launchers, and readily interchangeable weapons modules.

Regenerative Weapons

Regenerative weapons technology offers a major opportunity for mission performance improvement and payload enhancement. Transforming the submarine's abundant electric power into directed energy of different forms has the potential to greatly improve the submarine's self-defense capabilities. Technologies such as pulsed energy, hydraulic vortices, and destructive jets should be investigated for their effectiveness against mines and incoming torpedoes.

Short-range Antiship or Antiair Weapons Systems

Short-range antiship or antiair weapons systems are needed for use against maritime patrol-type aircraft or ASW helicopters and against small shallow-draft surface craft that are unsuitable torpedo targets (e.g., fast-attack craft, drug runners, and blockade and arms control violators). Supporting technologies include encapsulation and launch, missile direction and guidance, and acoustic signature reduction.

Navy Tactical Missile Systems and Missile Defense Systems

Navy tactical missile systems and missile defense systems will be in the payload of future submarines. Technology support for these future missions includes launcher technology, smart warheads (e.g., "brilliant" antitank weapons), deep-penetrating warheads, and CEC-like command-and-control systems.

Undersea Weapons Defense System

An undersea weapons defense system will be needed to mitigate the threat of advanced-capability torpedoes. An integrated system combining autodetection and alert, automated execution, jammers and deception devices (e.g., decoys), and hard-kill counterweapons should provide a robust solution. Such a system may also be effective against hostile submarines in close-in encounters or melees.

Payload Technologies to Support Unmanned and/or Autonomous Underwater Vehicles

Unmanned underwater vehicles (UUVs) and autonomous underwater vehicles (AUVs) will provide future submarines with a variety of new mission capabilities such as remote mine reconnaissance and location, environmental and operational intelligence collection, off-board sensing, seabed sensor deployment, and acoustic source positioning.

Platform technologies required to support these vehicles include automated launch and recovery systems, maintenance and energy replenishment techniques, mission planning and control systems, and secure underwater communications links for launch or recovery, control, data transmission, navigation, and rendezvous. Critical technologies for the vehicles themselves are advanced guidance and control and increased energy density (endurance), for example, advanced thermal and hybrid thermal-electrical concepts utilizing metal fuels. Technologies that enable submarines to support UUV or AUVs will generally apply to hosting manned vehicles such as the advanced SEAL delivery system and future manned minisubmarines. This subject is discussed further in the section on off-board vehicles.

Payload Technologies to Support Ground Forces

Marine Corps or special operations forces represent a payload that provides the submarine with a versatile and powerful capability for multiple missions: reconnaissance, sabotage, mine location and clearance, target designation, and so forth. Most of the technologies listed that support UUVs or AUVs are also applicable to supporting the missions of special operations forces. Additional requirements are for automated and quiet lock-out or lock-in of personnel and their vehicles, stealthy

surface launch and recovery of large numbers of troops, electromagnetic and acoustic LPI communications, and integrated mission planning and control.

Recommendation

Until recently, the submarine's payload has been restrained by continued reliance on the 21-in. torpedo tube. Aggressive action should be undertaken to develop a flexible, modular submarine payload system that can accommodate a variety of weapons, such as the family of weapons discussed elsewhere in this report, as well as off-board vehicles and other deliverables.

Power Density

The immediate goal of increasing power density is not necessarily reduction of submarine size, since displacement is an output, not an input, of the military requirements-based design process. Rather, the goal is enhancement of submarine stealth, affordability, and mobility, each of which will benefit from power plant space and weight reductions. A focused, integrated, and continuing program of both basic research and engineering development is required to achieve savings in weight and space for application to advances in payload, hull design, signature reduction, producibility, and maintenance.

Electric Drive

Electric drive offers the promise of substantial improvement in submarine stealth. It also provides greater flexibility in propulsion machinery arrangement. Implementation of electric drive could facilitate a reduction in size of the submarine while maintaining or improving stealth and hydrodynamic shaping; if a reduction in size evolved, it could also effect a reduction in the propulsion power required. Reduction in the space necessary for propulsion equipment could also free space for improved operational capabilities. Electric drive should be pursued vigorously.

Superconducting Motors and Generators

Conservation of significant space and weight is the primary objective of applying superconductivity in propulsion or ship's power motors and generators. Although the practical application of superconductivity is not yet feasible, some experts believe that with applied effort, superconducting motors and generators can be developed for submarines before the midpoint of the period from 2000 to 2035. Technical issues that will affect the application of superconductivity to submarines include nonacoustic EMI detectability, reliability, cryogenic system acoustics, high-flux density, and quiet motor design.

Solid-state Power Electronics

Power electronics enable practical electric drive systems and provide improved system control. Ongoing power technology advancements and advances in metal oxide semiconductor technology, such as those that enable the development of power electronic building blocks, will allow more sophisticated power distribution systems and greatly improve the power density of practical electric drive systems.

Power Plant Simplification

Subsequent to the initial operation of *Nautilus* there have been concerted efforts to reduce the number of plant components, as well as the controls and instrumentation associated with both primary and secondary sections of submarine nuclear power plants. The NSSN design has realized significant reductions in the volume of the engineering plant compared to that of the 688I class or the *Seawolf*, while maintaining *Seawolf* levels of quieting. Further major progress may be possible with elimination of the diesel engine, snorkel system, and storage battery through introduction of high-power-density, air-independent alternative power sources. Simplifying auxiliary systems such as air conditioning, hydraulics, and high-pressure air can also serve to reduce the propulsion and ship service components' fraction of total weight and volume, as well as the maintenance required.

Advanced Technology Alternative Reactor Designs

Studies by the Navy Nuclear Propulsion Directorate have shown that an advanced technology reactor may be realized in the 2035 time frame with a continuing and focused R&D effort aimed at significant improvement in both the heat source and the energy transfer mechanics. A major technical challenge is providing materials of sufficient strength to be used at the high temperatures involved. The advantages include not only space and weight savings but also quieting and simplicity of power conversion.

Alternative Power Sources

The panel discussed both air-independent propulsion (AIP) and fuel cells with regard to the power requirements of submarines. Both have application to the auxiliary system of submarines, especially for off-board vehicles. On the other hand, the power available in the foreseeable future is not sufficient to provide the main propulsion power to support the speed, endurance, and multimission capabilities required of U.S. submarines. As an example, the fire control system power

required of the AIP-capable Swedish Gotland submarine is 75 kW; that of the 688I is 550 kW.

Conclusions

The study's Panel on Technology assessed various technologies for propulsion power using six attributes of merit: (1) functionality, (2) mobility, (3) supportability, (4) serviceability, (5) manpower requirements, and (6) overall cost. Nuclear power was rated better than the fuel cell in each category.[2] The Panel on Platforms, like the Panel on Technology, decided that nonnuclear propulsion is not appropriate for U.S. Navy submarines.

While striving for improvement in the various aspects of power density, electric drive holds great promise to improve submarine stealth and design and should be pursued vigorously.

Off-board Vehicles

The potential benefits of submarine-borne unmanned underwater vehicles and unmanned aerial vehicles are significant. These vehicles and their embedded or leave-behind sensors will provide a cost-effective, clandestine force multiplier that greatly extends the sensor range of the submarine, allows for presence in high-risk regions or inaccessible littoral areas, and provides both timely and accurate knowledge of the battle space. At the same time, use of off-board vehicles can reduce risk to the submarine and its crew. Unmanned vehicles have the capacity and potential to develop and enhance mine reconnaissance and neutralization, tactical oceanography, bathymetry or survey, surveillance and intelligence collection, counterproliferation, tagging, decoys and remote jammers, and ASW through embedded sensors, deployed sensors, and trip wires, and to serve as an active acoustic source.

The technical issues that should be addressed to enable the development of capable low-cost vehicles include power density, duplex communications, guidance and control, geophysical and gravity field sensors, and stealth. Ultimate decisions will have to focus on expendability and reliability.

Unmanned Underwater Vehicles

Programs are extant today that will produce off-hull mine reconnaissance systems by about the year 2010. The systems will be either tethered or nontethered, will be preprogrammed, and will have search rates of 30 square nautical

[2] See Chapter 8, "Power and Propulsion," in *Volume 2: Technology* of this nine-volume series.

miles per day and an endurance of days. As technology develops, modular reconfigurability may provide optimum flexibility for a submarine-borne UUV. Also, as new sail designs are introduced, a UUV can be housed in the sail; such an accommodation would remove many constraints, including both size and payload, now imposed by storage, launch, and recovery limitations of UUVs. Larger and more varied payloads would result, including more numerous and capable sensors, weapons, communications and navigation suites, countermeasures, and nonacoustic systems. Larger sails to accommodate UUVs may add to overall drag or have other adverse performance effects. It may be possible to both accommodate larger and more varied payloads and improve performance and manueverability through the use of new hull forms.

Unmanned Aerial Vehicles

The basic ability to control UAVs from a submarine has been demonstrated, and this capability will be greatly improved in the future. The technological challenge will be to ensure tactical control and monitoring reliability of the UAV without compromising the host submarine's position. In addition, unless a vehicle can be developed with a cost-to-benefit ratio low enough to warrant expendability, a practical means of recovery without unacceptable compromise of submarine covertness is also required.

Conclusion

Off-board vehicles offer the potential to greatly expand the submarine's battle space. To date, the development of UUVs and UAVs has been inhibited by the decision to launch or recover them through the 21-in. torpedo tube. Technical measures to remove the 21-in. launch restriction in conjunction with the development of more flexible payload systems discussed above would enable more rapid development and deployment of off-board systems.

SUMMARY AND CONCLUSIONS

A conclusion of the Navy-21 study completed in 1988 states: "Submarines with increased capabilities could become major, multimission capital ships of the fleet . . . driven by the need to reduce vulnerability of forces . . . and by the opportunities offered by advanced missilery and quiet submarine technology . . . ."[3] This statement by the Navy-21 panel was remarkably prescient and has been

[3] Naval Studies Board. 1988. *Navy-21: Implications of Advancing Technology for Naval Operations in the Twenty-First Century, Volume 1: Overview,* National Academy Press, Washington, D.C., p. 41.

largely confirmed by submarine tactical and technological development over the past decade.

While maintaining the submarine-unique surveillance, intelligence collection, and ASW missions of the Cold War, the utility of SSNs is recognized such that they are now integrated fully into Navy battle groups and their land-attack missiles are included in joint precision strike packages. The adaptation of the Army Tactical Missile System will permit SSNs to deploy tactical missiles for conventional deterrence and fire support to ground forces. This expansion of submarine missions, foreseen by the Navy-21 study, has been enabled by the steady insertion of new technology ranging from satellite navigation and HDR communications to advanced digital processing of acoustic and targeting data. At the same time, submarine operational availability has been increased and lifetime costs have been reduced by condition-based maintenance concepts and new reactor cores that last through the service life of the ship without refueling.

This retrospective view is important because it illustrates the fact that although there have been no dramatic breakthroughs in submarine technology since *Navy-21*, the steady infusion of new technology into nearly all aspects of submarine performance has resulted in a substantial increase in submarine warfighting effectiveness. Indeed, the dramatic improvement in operational capability over a period of 20 years, from the first submarine of the *Los Angeles* SSN 668 class to the final improved SSN 688 (688I) and then to the impressive *Seawolf* (SSN 21), could have been neither foreseen nor accomplished had a policy of waiting for a major technological breakthrough prevailed. This experience confirms the wisdom of maintaining a steady and stably funded submarine technology development program, sharply focused on mission effectiveness and prepared to promptly insert the products of that program into the submarine force through forward fit and/or backfit as appropriate. Thus, even while aggressively striving for breakthroughs over the next 40 years, such as direct conversion of nuclear energy to electrical energy, the policy of actively refreshing and inserting new technology should be sustained.

In looking to the future, it appears certain that the expansion of submarine missions will continue, driven by the push of emerging technology, with the catalyst of the increasing vulnerability of nonstealthy naval forces operating anywhere including forward areas. Thus, freed from the primary Cold War focus on strategic deterrence and ASW, imaginative submarine design concepts will be required to support these expanded missions, new sensors, weapons, and off-board vehicles. Bringing new and expanded missions to operational reality will require the steady application of technology focused on military objectives and integrated across the submarine platform. Some specific enabling technology areas should be pursued vigorously to ensure the success of this vision:

- *Stealth technology.* Acoustic and nonacoustic stealth will remain the fundamental characteristic that enables all submarine missions. Aggressive and

integrated development of all facets of submarine stealth technology is essential to maintaining the submarine's stealth advantage and its continued operational effectiveness.

- *Payload technology.* As the scope and depth of submarine missions expand, the development of technology to carry, launch, recover, and deliver the submarine's varied payload gains in importance. Stealth, flexibility, modularity, commonality, and affordability are important characteristics to be sought in developing new payload technology.
- *Sensors and connectivity.* The submarine's ability to sense, process, and fuse information in all operating environments and to network fully with the naval, joint, and national command structure is becoming increasingly vital to its operational effectiveness. The application and integration of fiber optics, acoustics, lasers, high-speed computers, and other new techniques will be required to achieve the necessary improvements in sensors and connectivity.
- *Power-density technology.* Increasing the power density in submarine propulsion, auxiliary power, and in off-board vehicles offers substantial improvement in platform performance, system simplification, and affordability. The direct and indirect benefits of increased power density suggest a substantial investment in this area. Electric drive is an especially promising propulsion technology and is worthy of strong support.
- *Off-board vehicles.* The employment of off-board vehicles to expand significantly the submarine's battle space holds great promise. A broad range of technology improvements is required to achieve the operational potential these vehicles offer; they include automated launch and recovery, vehicle guidance and control, submarine-to-vehicle data links, and vehicle endurance.
- *Submarine architecture.* The broad technology category of submarine architecture brings together a wide range of science, technology, materials, and processes to integrate them into a submarine design that is efficient to produce, amenable to future improvement, affordably manned and maintained, and above all, operationally superior. By using an integrated product development approach and applying the power of advanced digital design systems, these diverse technologies and requirements can be combined, examined synergistically, and tested in virtual reality and/or reduced-scale prototypes to develop submarines that will best satisfy the expanding range of operational requirements.

Considering the vast changes that have evolved in the past 40 years and the rapid pace of technology in just the last few, the panel would be presumptuous to assume that it could predict, with more than a modicum of certainty, even the basic composition of the Navy of 2035. Obviously, knowledge of the nature and location of the most probable potential adversaries is an even more remote possibility. There are technologies about which we have not thought, yet they may be dominant 40 years from now. However, based on current trends and the opportu-

nities that technology seems to offer, a vision emerges of future naval forces that are dispersed, flexible, interconnected, and equipped with sensors and weapons to enable standoff engagements. The paramount characteristic of any future force will be stealth, the ability to dominate the battle space with minimum vulnerability.

It is certain then that submarines, as the original and most viable stealth platforms, will be indispensable elements of future naval forces, even though their precise size or design can be speculated on only in general terms. Concepts for future submarines can range from large mother submarines hosting multimission minisubmarines to undersea tugboats pushing or towing undersea barges with mission-tailored payloads of weapons or supplies. Regardless of the specific undersea concepts that emerge, the technologies examined in this study—and others yet to come—will be essential to support their development. Through these technologies, the United States can design and build the most capable submarines possible to satisfy the long-term security requirements of our maritime nation. To this end, it is important that the U.S. Navy actively stimulate the development of submarine technology by promoting a broad and imaginative vision of future submarine naval warfare capabilities.

APPENDIXES

A

Terms of Reference

CHIEF OF NAVAL OPERATIONS

28 November 1995

Dear Dr. Alberts,

In 1986, at the request of this office, the Academy's Naval Studies Board undertook a study entitled "Implications of Advancing Technology for Naval Warfare in the Twenty-First Century." The Navy-21 report, as it came to be called, projected the impact of evolving technologies on naval warfare out to the year 2035, and has been of significant value to naval planning over the intervening years. However, as was generally agreed at the time, the Navy and Marine Corps would derive maximum benefit from a periodic comprehensive review of the implications of advancing technology on future Navy and Marine Corps capabilities. In other words, at intervals of about ten years, the findings should be adjusted for unanticipated changes in technology, naval strategy, or national security requirements. In view of the momentous changes that have since taken place, particularly with national security requirements in the aftermath of the Cold War, I request that the Naval Studies Board immediately undertake a major review and revision of the earlier Navy-21 findings.

The attached Terms of Reference, developed in consultation between my staff and the Chairman and Director of the Naval Studies Board, indicate those topics which I believe should receive special attention. If you agree to accept this request, I would appreciate the results of the effort in 18 months.

Sincerely,

J. M. BOORDA
Admiral, U.S. Navy

Dr. Bruce M. Alberts
President
National Academy of Sciences
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Enclosure

TERMS OF REFERENCE

TECHNOLOGY FOR THE FUTURE NAVY

The Navy-21 study (Implications of Advancing Technology for Naval Warfare in the Twenty-First Century), initiated in 1986 and published in 1988, projected the impact of technology on the form and capability of the Navy to the year 2035. In view of the fundamental national and international changes -- especially the Cold War's end -- that have occurred since 1988, it is timely to conduct a comprehensive review of the Navy-21 findings, and recast them, where needed, to reflect known and anticipated changes in the threat, naval missions, force levels, budget, manpower, as well as present or anticipated technical developments capable of providing cost effective leverage in an austere environment. Drawing upon its subsequent studies where appropriate, including the subpanel review in 1992 of the prior Navy-21 study, the Naval Studies Board is requested to undertake immediately a comprehensive review and update of its 1988 findings. In addition to identifying present and emerging technologies that relate to the full breadth of Navy and Marine Corps mission capabilities, specific attention also will be directed to reviewing and projecting developments and needs related to the following: (1) information warfare, electronic warfare, and the use of surveillance assets; (2) mine warfare and submarine warfare; (3) Navy and Marine Corps weaponry in the context of effectiveness on target; (4) issues in caring for and maximizing effectiveness of Navy and Marine Corps human resources. Specific attention should be directed, but not confined to, the following issues:

1. Recognizing the need to obtain maximum leverage from Navy and Marine Corps capital assets within existing and planned budgets, the review should place emphasis on surveying present and emerging technical opportunities to advance Navy and Marine Corps capabilities within these constraints. The review should include key military and civilian technologies that can affect Navy and Marine Corps future operations. This technical assessment should evaluate which science and technology research must be maintained in naval research laboratories as core requirements versus what research commercial industry can be relied upon to develop.

2. Information warfare, electronic warfare and the exploitation of surveillance assets, both through military and commercial developments, should receive special attention in the

review. The efforts should concentrate on information warfare, especially defensive measures that affordably provide the best capability.

3. Mine warfare and submarine warfare are two serious threats to future naval missions that can be anticipated with confidence, and should be treated accordingly in the review. This should include both new considerations, such as increased emphasis on shallow water operations, and current and future problems resident in projected worldwide undersea capability.

4. Technologies that may advance cruise and tactical ballistic missile defense and offensive capabilities beyond current system approaches should be examined. Counters to conventional, bacteriological, chemical and nuclear warheads should receive special attention.

5. The full range of Navy and Marine Corps weaponry should be reviewed in the light of new technologies to generate new and improved capabilities (for example, improved targeting and target recognition).

6. Navy and Marine Corps platforms, including propulsion systems, should be evaluated for suitability to future missions and operating environments. For example, compliance with environmental issues is becoming increasingly expensive for the naval service and affects operations. The review should take known issues into account, and anticipate those likely to affect the Navy and Marine Corps in the future.

7. In the future, Navy and Marine Corps personnel may be called upon to serve in non-traditional environments, and face new types of threats. Application of new technologies to the Navy's medical and health care delivery systems should be assessed with these factors, as well as joint and coalition operations, reduced force and manpower levels, and the adequacy of specialized training in mind.

8. Efficient and effective use of personnel will be of critical importance. The impact of new technologies on personnel issues, such as education and training, recruitment, retention and motivation, and the efficient marriage of personnel and machines should be addressed in the review. A review of past practices in education and training would provide a useful adjunct.

9. Housing, barracks, MWR facilities, commissaries, child care, etc. are all part of the Quality of Life (QOL) of naval personnel. The study should evaluate how technology can be used to enhance QOL and should define militarily meaningful measures of effectiveness (for example, the impact on Navy readiness).

10. The naval service is increasingly dependent upon modeling and simulation. The study should review the overall architecture of models and simulation in the DoD (DoN, JCS, and OSD), the ability of models to represent real world situations, and their merits as tools upon which to make technical and force composition decisions.

The study should take 18 months and produce a single-volume overview report supported by task group reports (published either separately or as a single volume). Task group reports should be published as soon as completed to facilitate incorporation into the DoN planning and programming process. An overview briefing also should be produced that summarizes the contents of the overview report, including the major findings, conclusions, and recommendations.

B

Acronyms and Abbreviations

AEW	Airborne early warning
AIP	Air-independent propulsion
ALAFS	Advanced Lightweight Affordable Fuselage Structures (program)
ASW	Antisubmarine warfare
ATD	Advanced technology demonstration
ATP	Advanced technology program
AUV	Autonomous undersea vehicle
B&V	Blohm and Voss
CADAM	Computer-aided design and manufacturing
CAVES	Conformal acoustic velocity sensing
CEC	Cooperative engagement capability
CFD	Computational fluid dynamics
C^4I	Command, control, communications, computing, and intelligence
CIC	Combat information center
CLIDCS	Component-level intelligent distributed control systems
CNO	Chief of Naval Operations
COTS	Commercial off-the-shelf
CSA	Common support aircraft
CTOL	Conventional takeoff and landing
CV	Aircraft carrier
DARPA	Defense Advanced Research Projects Agency
DOD	Department of Defense

EM	Electromagnetic
EMI	Electromagnetic interference
EMP	Electromagnetic pulse
EMTC	Electromagnetic turbulence control
EW	Electronic warfare
GPS	Global Positioning System
HDR	High data rate
HIP	Hot isostatic press
HSLA	High-strength, low-alloy (steel)
IGBT	Insulated gate bipolar transistor
IHPTET	Integrated High Performance Turbine Engine Technology (program)
IPS	Integrated power system
IR	Infrared
JSF	Joint Strike Fighter (program)
LAN	Local area network
LHD	Amphibious assault ship
LON	Local operating network
LPI	Low probability of intercept
ManTech	Manufacturing technology development program
MCT	Metal oxide semiconductor-controlled thyristor
MEMS	Microelectromechanical systems
MIDS	Modular isolated deck structure
NASA	National Aeronautics and Space Administration
NAVAIR	Naval Air Systems Command
NAWC	Naval Air Warfare Center
NMD	National Missile Defense
NSSN	New nuclear-powered attack submarine
OOTW	Operations other than war
PEBB	Power electronic building block
R&D	Research and development
RF	Radio frequency
RTM	Resin transfer molded (spars and fusilage frames)
SCWO	Supercritical water oxidation
SEAL	Sea, air, land team
SMS	Smart materials and structures (technologies)
SSBN	Nuclear-powered ballistic missile submarine
SSN	Nuclear-powered attack submarine
STOL	Short takeoff and landing
STOVL	Short takeoff and vertical landing
TMD	Theater missile defense
UAV	Unmanned aerial vehicle
USMC	U.S. Marine Corps

UUV	Unmanned underwater vehicle
VA	Attack squadron
VF	Fighter squadron
VLS	Vertical launch system
VP	Patrol squadron
VSTOL	Vertical and short takeoff and landing
VTOL	Vertical takeoff and landing